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RAYLEIGH WAVES FROM HIGH GAIN LONG-PERIOD STATIONS: SIGNAL EXTRACTION; AMPLITUDE DETERMINATION; AND SEPARATION OF OVERLAPPING WAVE TRAINS

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(continued)

20.

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The method also provides high resolution of co-located events with short time separation, or widely spaced events with Rayleigh waves arriving nearly simultaneously at a single station. Examples include: (1) clear separation, amplitude determination, and so forth, at stations KIP and MAT of two $M_s = 6.5$ earthquakes located 0.7^{o} and 145 sec apart (off the coast of central Chile); (2) clear separation at station KIP of a Novaya Zemlya event $M_b = 4.8$ from interfering Rayleigh waves of an $M_b = 5.0$ Kermadec Island earthquake arriving 120 to 140 sec prior to the searched event, with almost complete elimination of interference on the summed vertical and radial processed components; and (3) clear separation at station KIP of two co-located $M_b = 4.4$ and 4.5 earthquakes, 6 minutes apart, from the area off the coast of Chile, determination of their amplitudes, and so forth, in the presence of interfering Rayleigh waves from two Central Alaskan earthquakes, the first ($M_b = 4.1$) arriving 15 minutes prior to the first Chilean Rayleigh wave and the second between the two Chilean arrivals.

The threshold reached (10 and 25 digital units, p-p) for stations MAT and KIP at 98^{o} and 155^{o}, respectively, corresponds to an M_s ~ 3.3 and probably can be improved further.

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Rayleigh Waves from High Gain Long-Period Stations: Signal Extraction; Amplitude Determination; and Separation of Overlapping Wave Trains

by

Eduard Berg

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RAYLEIGH WAVES

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University of Hawaii

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Contents

ABSTRACT

Rayleigh waves are extracted and amplitudes (with standard errors) and origin time (within a few seconds) determined by use of reference earthquakes or explosions, high pass (HP) and normalized matched (NM) (or correlation) filters, and the oceanic group-velocity dispersion between 38 and 18 seconds. For a signal-to-noise ratio between 0.2 and 0.1 on the original single-component records, amplitudes for Rayleigh waves over oceanic paths of 155° at station MAT and 98° at station KIP have been determined as 12 mμ (10 digital units) and 24 mμ (25 digital units) peak-to-peak (p-p), respectively, with a standard error of less than 11%. In each case the processed signal is the highest in a half-hour processed record.

The method also provides high resolution of co-located events with short time separation, or widely spaced events with Rayleigh waves arriving nearly simultaneously at a single station. Examples include: (1) clear separation, amplitude determination, and so forth, at stations KIP and MAT of two $M_s = 6.5$ earthquakes located 0.7° and 145 sec apart (off the coast of central Chile); (2) clear separation at station KIP of a Novaya Zemlya event $M_b = 4.8$ from interfering Rayleigh waves of an $M_b = 5.0$ Kermadec Island earthquake arriving 120 to 140 sec prior to the searched event, with almost complete elimination of interference on the summed vertical and radial processed components; and (3) clear separation at station KIP of two co-located $M_b = 4.4$ and 4.5 earthquakes, 6 minutes apart, from the area off the coast of Chile, determination of their amplitudes, and so forth, in the presence of interfering Rayleigh waves from two Central Alaskan earthquakes, the first ($M_b = 4.1$) arriving 15 minutes prior to the first Chilean Rayleigh wave and the second between the two Chilean arrivals.

The threshold reached (10 and 25 digital units, p-p) for stations MAT and KIP at 98° and 155°, respectively, corresponds to an $M_s = 3.3$ and probably can be improved further.

INTRODUCTION

Relative amplitude of surface waves that are generated for a given short-period P-wave signal (Press et al., 1963; Brune et al., 1963; Ericsson, 1970; Basham and Whitham, 1971) is one of the most useful discriminants to distinguish earthquakes from explosions. Short-period P waves are readily detected for small events, but for small events the determination of the surface wave magnitude using the Rayleigh waves is much more difficult, especially when the signal amplitudes are smaller than the noise level at a single or even at an array of long-period stations. Additional difficulties arise when interfering surface waves must be separated, generated either from multiple arrivals (lateral refractions and reflections from continental margins), from the same event, or from other events at nearly the same location and a few minutes apart or at distant locations.

Alexander and Rabenstine (1967a, 1967b) used matched-filter techniques to improve signal-to-noise (S/N) ratio for LASA,* LRSM,** and observatory stations in addition to pre band-pass filtering. The method compared a known Rayleigh wave signal with the unknown signal from the same area by cross correlation, but was usually applied to seismograms with S/N ratios above 1 and never normalized. The beam-formed matched-filter S/N ratio for 13 LASA stations was 17 db above the mean S/N ratio for the individual band-pass filtered seismograms; for 13 LRSM stations it was 15 to 16 db above the mean S/N ratio of band-pass filtered seismograms. However, Alexander and Rabenstine's approach (1967b, p. 14) did not allow reliable signal amplitude estimates where signals were below the highest noise peaks; but they showed from synthetic records that an S/N ratio of 0.35 still allowed extraction of the teleseismic surface waves. This report presents a reliable method of determining surface wave signal amplitude (and standard error) that works at S/N ratios between 0.2 and 0.1) for single seismograms.

McDonald et al. (1974) extended the Alexander-Rabenstine approach by synthesizing a matched filter with the same average group-velocity dispersion as three Greenland Sea and one Chinese events, as recorded at Grand Saline, Texas. They applied the filter successfully to the small earthquakes in the Sino-Soviet land mass, taking full advantage of the long-period surface wave guide over the pole. The wave guide extends to periods of about 75 sec and generates a well-dispersed wave train. A detection threshold of $M_s = 3.5$ was obtained for the Rayleigh waves arriving at the single vertical component at Grand Saline through the polar wave guide, an

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*Large Aperture Seismic Array

**Long Range Seismic Measurement

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M_b = 4.5 equivalent for focal depth less than 50 km. Their use of the chirp filter between 75 and 20 sec made the detection in the wave guide beam (about 45°) independent of a specific reference event, but did not seem to allow separation of multiple events from multiple arrivals (from a single event), nor to provide amplitude information from the correlation processing.

Capon et al. (1969) and Capon (1970) successfully increased the S/N ratio for Rayleigh waves (at LASA) using noise prediction, matched (chirp) filtering, and beam-forming in the frequency-wave number domain. Later, Capon and Evernden (1971) applied this method to the 40-sec Rayleigh waves. Only the vertical components were used, since the horizontal instruments were too noisy to apply the surface wave discriminant at low S/N ratios. Capon et al. (1969, table 2) obtained total average S/N ratio gains of 22 db (for matched chirp filter, noise prediction filter, and beam-forming for 17 seismometers). Subsequently, Capon and Evernden (1971) considered the resolving limits of the method (at 40 sec) as to azimuth and time separation, and found that events from almost opposite directions (such as from the Kuril Islands and from Ecuador), simultaneous arrivals, and power level differences of 6 db (average) could be separated. With increasing time difference, larger level differences could be resolved with an average relative amplitude of between 26 and 30 db at a time separation of more than 10 minutes, the actual maxima and minima of the resolvable level differences depending on the die-off character of the 40-sec Rayleigh wave (Capon and Evernden, 1971, Fig. 12).

While the use of reference earthquakes (or explosions) requires more detailed information than does the chirp matched-filter method, the advantages of the former are that the signal amplitude (and its standard error) can be obtained. Multiple arrivals from the same source with different travel paths are included in the (earthquake reference) matched filter, and therefore do not appear as distinct arrivals on the correlation trace. The matched chirp filter however shows these multiple arrivals and is unable to distinguish them from multiple events. In addition use of a normalized correlation (= 1 for perfect signal match) permits the specification of decision levels, recognition of defective recording traces and other erroneous signatures that are not readily computerized, and application of statistical measures. As an example, the Rayleigh wave for an M_b = 4.5, M_s = 3.3 Chilean earthquake has been extracted at the MAT (Δ = 17000 km) high gain long-period vertical component (after preliminary high-pass filtering); the amplitude was determined as 9.4 digital units (peak-to-peak) (about 12 mμ at 30 sec). The correlation peak is the highest in the 30-minute period scanned. The noise background at the time was between 90 and 100 digital units (p-p) on the original unfiltered record (see Outputs 4 and 4/40 at end of report).

In this study, a systematic attempt was made to determine the influence of the length of the reference record, and of the high-pass prefiltering, on the results of single and combined vertical and horizontal component processing. The best detection and separation from a single station were achieved by summing the vertical and radial Rayleigh wave components after 40-sec high-pass and matched filtering (in that order). However, so far we have considered mostly oceanic paths, and have taken advantage of the well-dispersed oceanic Rayleigh waves for periods shorter than 40 sec, the worldwide noise minimum, and the maximum gain of the high gain long-period stations between 30 and 40 sec (Murphy <u>et al.</u>, 1972).

NORMALIZED MATCHED FILTER

The source, transmission path, and instrument response function determine the seismic signal recorded on a seismograph. When using a reference earthquake as the matched-filter impulse response, it is tacitly assumed that the source function (amplitude and phase) can be simply scaled up or down (the focal mechanism remaining more or less constant) while the path and instrument functions remain constant. This differential approach, which eliminates the need for detailed knowledge of the transfer functions of the transmission path and receiver, has been applied during other investigations (Berckhemer, 1962; Alexander and Rabenstine, 1967a and b; and lately by Weidner and Aki, 1973). Several papers (Berckhemer, 1962; Aki, 1967; Savage, 1972; Haskell, 1964; Brune, 1968) give theoretical fault models and experimental data for the spectral amplitude density as a function of fault parameters, such as rupture pattern in the fault surface, elastic and rupture velocities, and fault dimensions. All these investigations show that for $3 < M_s < 5.5$, the source spectrum is constant for periods longer than 20 sec (Aki, 1967, Figs. 3 and 4; or Berckhemer, 1962, Fig. 11d). We therefore feel justified in assuming a constant spectrum requiring only an amplitude scaling of the Rayleigh waves to be extracted for the earthquakes (of similar focal mechanism, area and depth), as long as the reference earthquake does not exceed $M_s = 5.5$. On the other hand, $M_s = 5.5$ assures a healthy S/N ratio for the reference earthquake on the high gain long-period station records if the Rayleigh wave is not contaminated by other surface wave trains. The assumption of similar focal mechanism is borne out by the fact that the correlation peaks always show a positive sign.

The basic formulas for the correlation traces are given in the Appendix; they present the cross correlation coefficient of the scanned record trace with respect to the reference trace (Crow <u>et al.</u>, 1960). A matched-filter response (after high pass filtering at 40 sec) is presented in Figure 2b for the Z component of the reference earthquake in the Kurils (Output 2/40). A perfect match would result in an output of "one" at the lag time of the beginning of the reference signal. The advantage of the normalized matched-filter output is that it permits determination of an absolute value for the maximum noise correlation with the reference signal (of a given length and area) which value, if exceeded, indicates the presence of a seismic (surface) wave. The correlation is formed between the reference and the record by incrementing lags. When a maximum correlation is found, this correlation time is taken as the start time of the hidden signal in the record (as plotted in the correlation trace above the record trace). To make the maximum correlation station independent for a given earthquake-station combination, the time labeling (on the correlation trace) is shifted

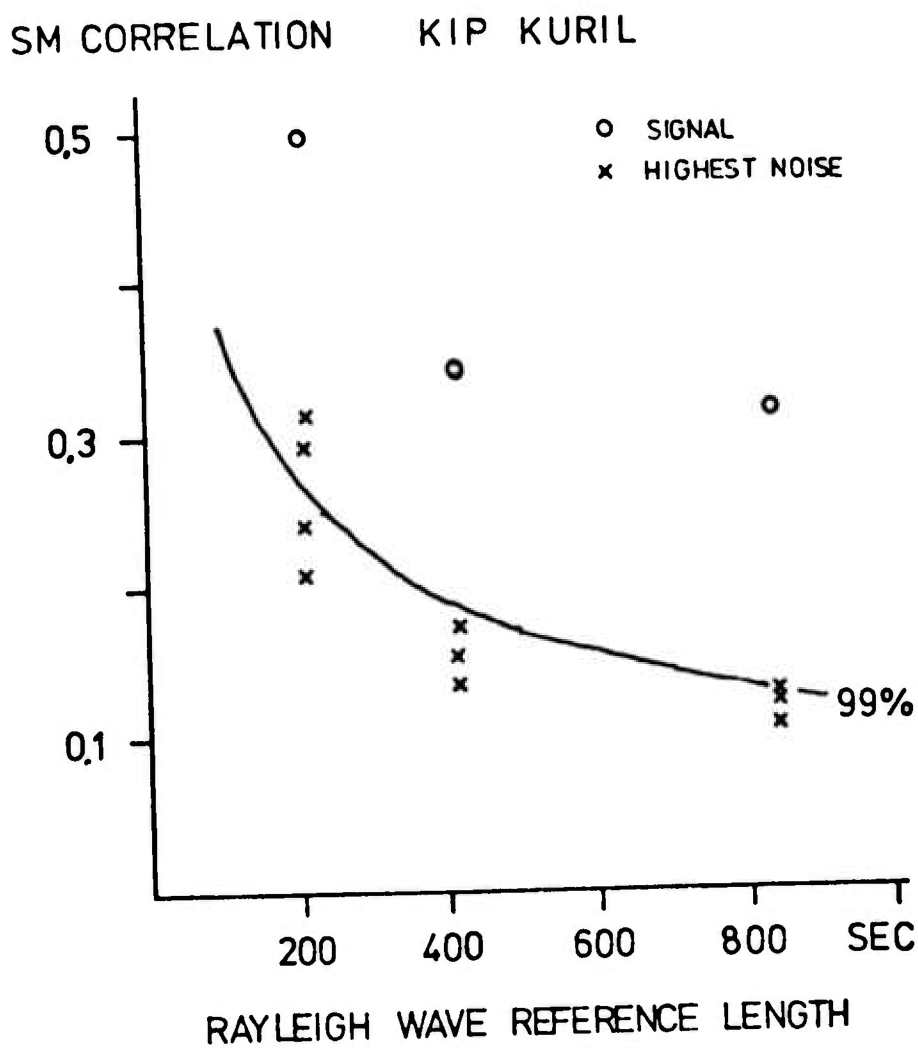

Fig. 1. One-third the sum of vertical, N-S, and E-W correlation traces as function of data length for the Kuril Islands earthquakes as recorded at KIP. For 99 per cent level, refer to text.

(to an earlier time) by the difference between the origin time and the start time of the reference earthquake trace. This insures that irrespective of the station used, the maximum correlation occurs near the scanned earthquake's origin time, assuring proper identification at several stations. Details of all earthquakes and explosions processed or mentioned are presented in the table on page 19.

An example from station MAT is given in Output 1. The fourth, seventh, and last traces are the Rayleigh wave portions of the Z, N-S, and E-W components of the reference earthquake. The third, sixth, and ninth traces are the scanned Z, N-S, and E-W records (note that the E-W component was not operating properly, since no signal is visible). The second, fifth, and eighth traces are the normalized matched filter outputs with scale from +1 to -1, and the "SM" (first) trace is one-third the sum of the three matched-filter traces. If only two components have been processed (such as vertical and radial) the SM trace is one-half the sum of the two correlation traces. Figure 1 shows the signal correlation coefficient obtained (for the same Kuril earthquakes recorded at KIP) as a function of the data lengths of the reference Rayleigh wave train, and the three or four highest (positive) noise peaks (for a half-hour scan). It is clear that they follow the statistical distribution. The 99 per cent line means that only 1 per cent of the population of correlation coefficients with values higher than indicated by that line are associated with data sets (six variables: three reference traces and their noise and three scanned traces and their noise) that do not show any relation. On the other hand, the decision level (to consider a correlation level as presenting a signal) depends on the reference data length. After this preliminary investigation, we always used an 841 data point (840 sec) reference section. These 14 minutes of reference section correspond to a variable portion of the group-velocity dispersion curve depending on station to epicenter distance, but seem to yield good results for extraction and S/N ratio of the correlation, since for the oceanic path they include the most dispersed portion of that curve up to over 10,000 km distance.

Since the relatively long reference section includes at least the early multiple arrivals (if they exist), they all will be condensed into the correlation peak to help separate it from other events. This is a distinct advantage of the reference earthquake matched-filter over the chirp-type filter (that usually shows the multiple arrivals as separate signals) in extracting small surface-wave events (as well as amplitude determinations).

AMPLITUDE DETERMINATION

Another disadvantage of the chirp-filter is its complete lack of attenuation and instrument response information, so that amplitude scaling is unobtainable. The reference earthquake matched-filter, by contrast, contains all this information and therefore is ideally suited for amplitude extraction. In addition, all the computational steps required to determine the correlation coefficient between the

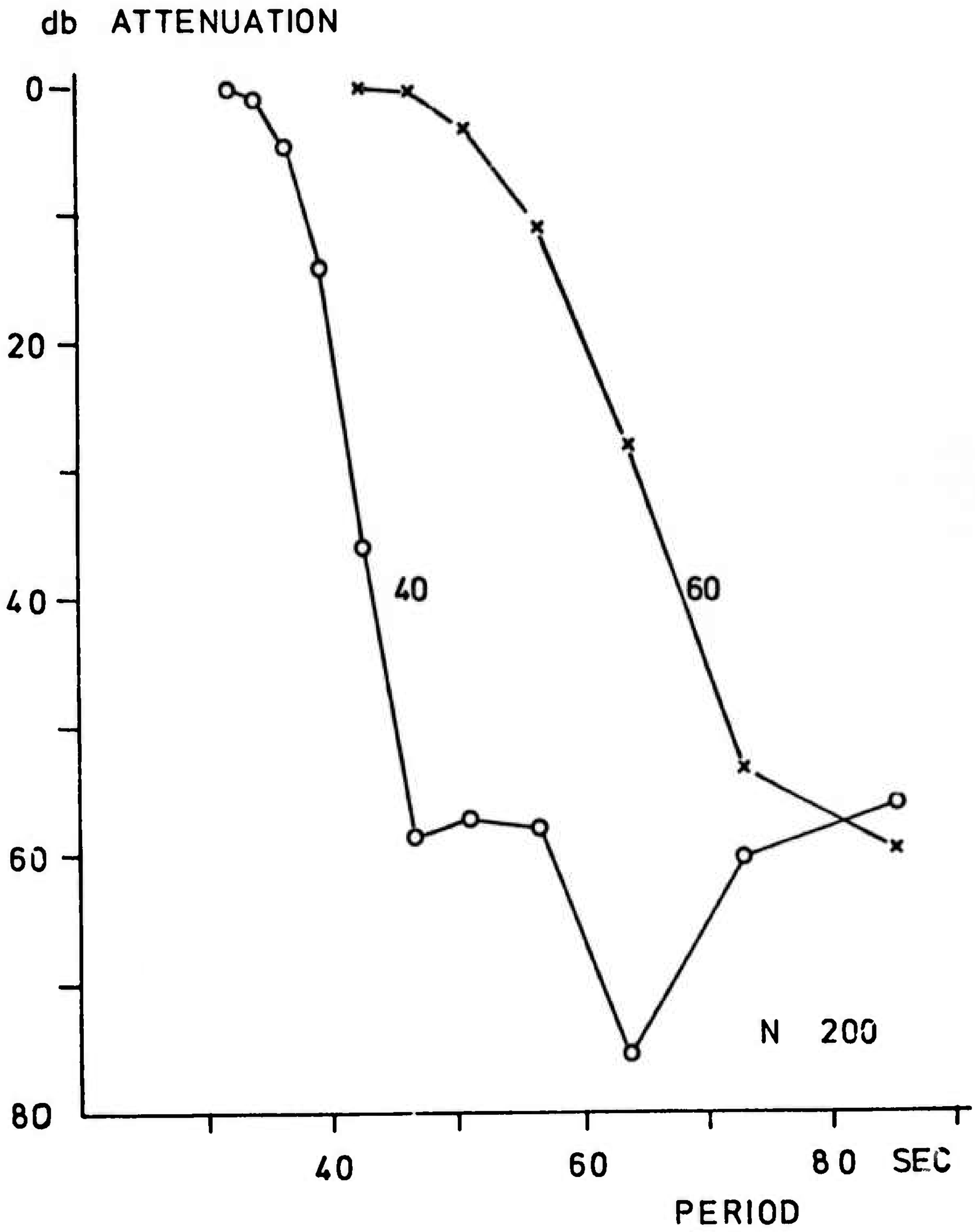

Fig. 2A. High pass filter attenuation for the 40-sec and 60-sec filters used. (For filter time functions, refer to the Appendix.)

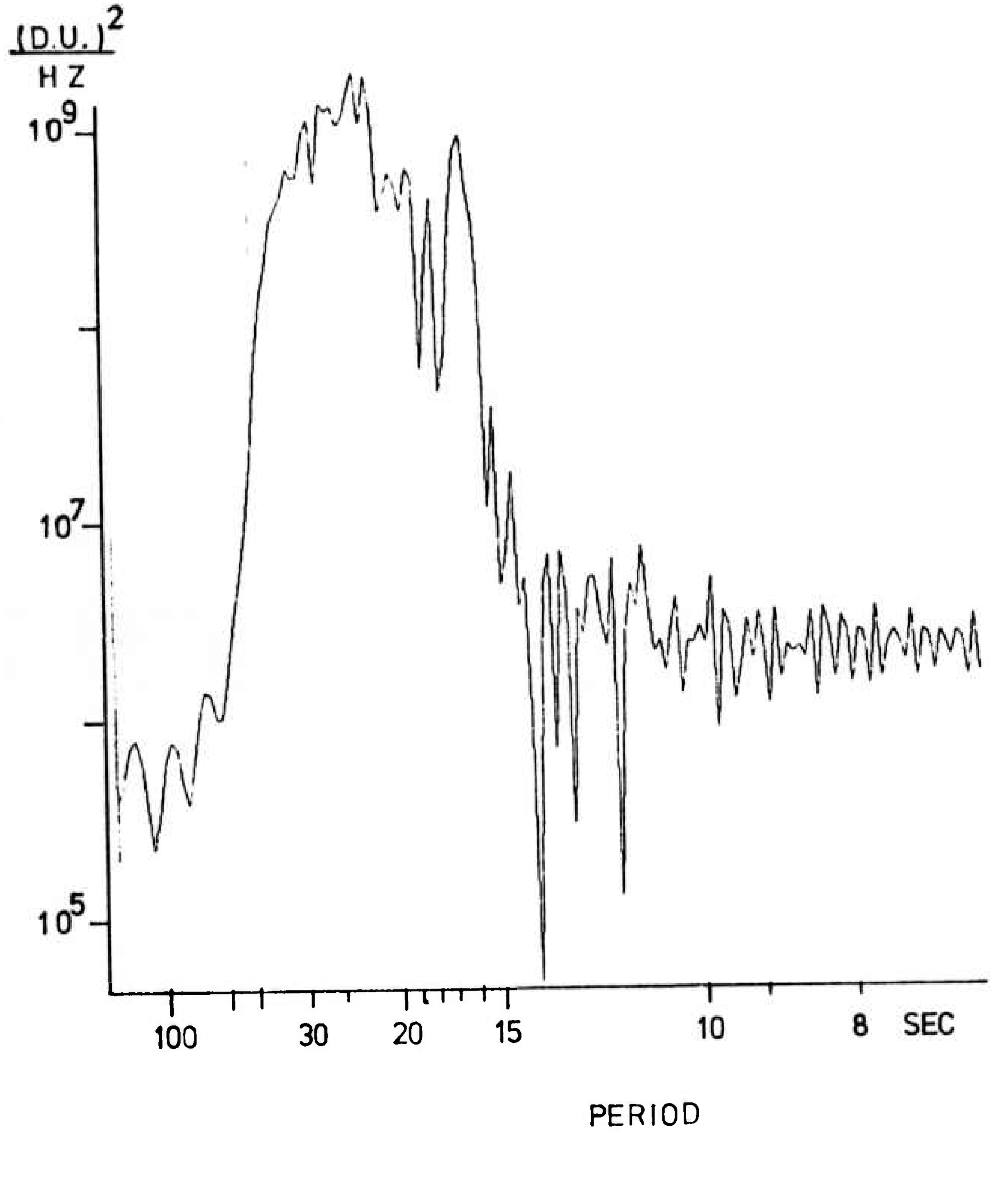

Fig. 2B. Power spectrum of the matched-filter time function of the KIP-Z Kuril Islands reference earthquake of Output 2/40 (not normalized). Note the reference also was HP, prefiltered at 40 sec.

scanned and reference trace contain all the information for determination of the relative amplitude and the standard error, since a simple linear relation between reference earthquake and scanned earthquake is assumed. Determining the relative amplitude involves finding the slope of the regression line of the scanned data (at time of maximum correlation) on the reference data and the standard error of the slope. (See Crow et al., 1960, p. 152).

Since the relative standard error of the slope is only a function of the reference length used and the correlation obtained, the decision on an extraction level (or the presence of a signal at a predetermined value of correlation) also sets the upper limit for the standard error in per cent of the amplitude. (Figure 7 gives the relative standard error as a function of the correlation coefficient obtained for a reference length of 841 data points; the corresponding formulas are presented in the Appendix.) This information (time of maximum correlation, slope = relative amplitude, standard error) was only printed out for the maximum positive correlation in each (usually half-hour) scan and was added at the end of the corresponding correlation in the output plots.

Since for nuclear explosions and their cavity collapse (and possibly aftershocks) a negative correlation is expected (and observed, see Output 8R), amplitude and error information should be obtained for the minimum correlation as well.

Simply taking the $\log_{10}$ of the slope (or the relative amplitude) gives the difference in M_s between the extracted and the reference earthquake. Since M_s for the reference earthquake can be determined as an average over many stations (or may include considerations for radiation patterns), the value determined for the scanned extracted earthquake is free of individual station corrections and appears to be very stable (see Fig. 6).

PREFILTERING

Most reference earthquakes (over the oceanic path used so far) showed the longest periods between 35 and 39 sec, and the noise appears large at longer periods, especially on the horizontal components of the high gain system. Therefore, high-pass filters with cutoff periods of 60, 50, 40, and 30 sec have been applied before matched filtering to determine improvement in correlation and the S/N ratio (filter characteristics are presented in Fig. 2A and 2B). The value used here is the (correlation signal peak)/(next highest positive noise peak) (C:SN) for a half-hour scan and a reference length of 840 sec, correlated after both the reference and the scanned trace have been high-pass filtered.

The general relation between the correlation and C:SN is depicted in Figure 3 for the earthquake from off the coast of Chile recorded at MAT and KIP and the Kuril Islands earthquake recorded at

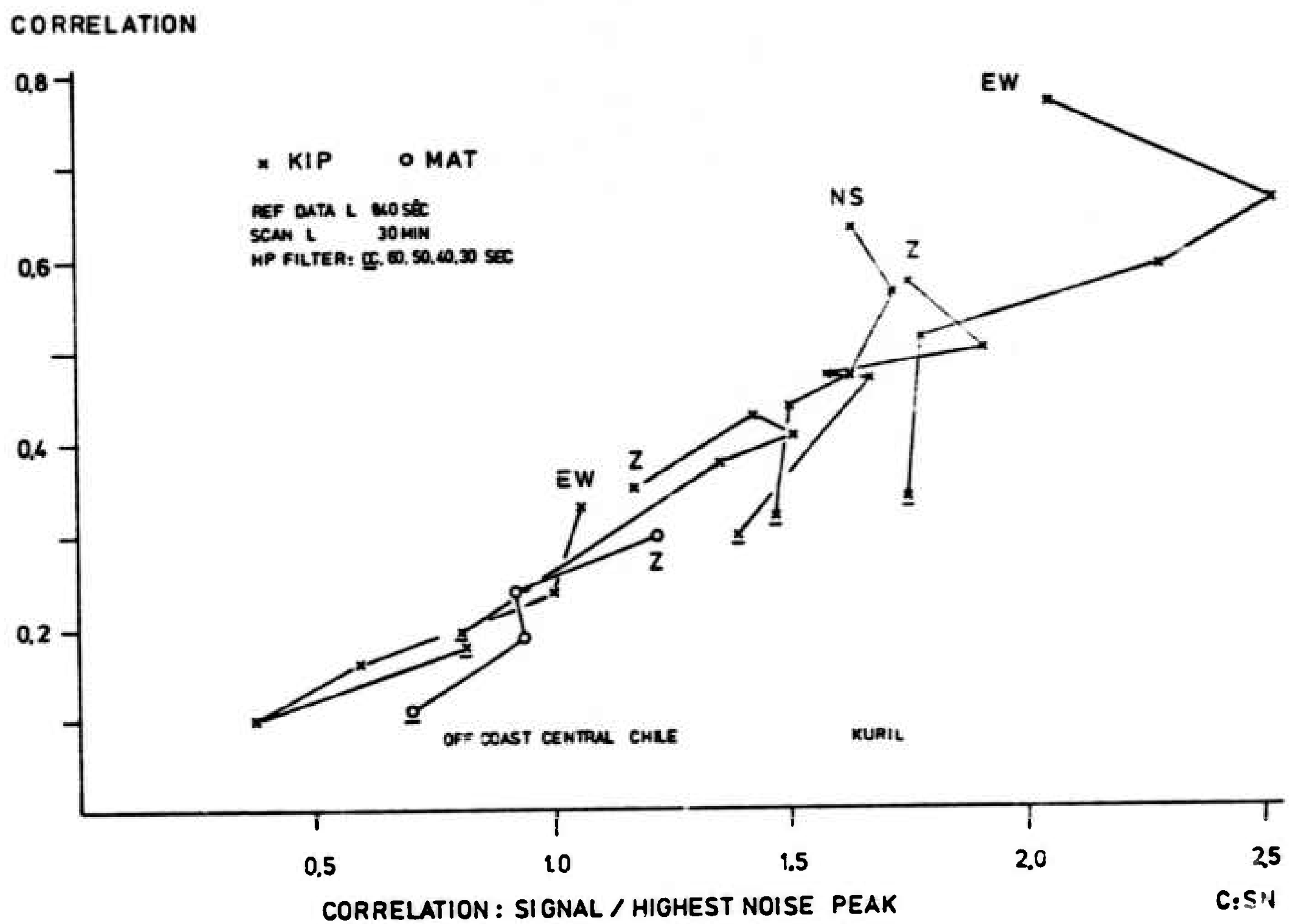

Fig. 3. Correlation coefficient (C) versus correlation signal noise (C:SN) for various HP filters. Increase in correlation results in improved amplitude determination; increase in C:SN, in improved detection. Pre high-pass filtering near 40 sec to 50 sec gives best results for pure oceanic travel path.

KIP (see table, p. 18). Underlined data points are values obtained without filter. The progress along a line corresponds to HP filters at 60, 50, 40, and 30 sec, except for the MAT-Chile Z trace where the last point corresponds to a 40-sec HP filter. It should be noted that placing a decision level for the presence of a signal at 0.3 for the correlation of a single trace (with 840-sec reference in a half-hour scan) seems to assume that the highest signal peak is not due to noise (or C:SN > 1 for all signals with C > 0.3). Note also how the progressive filtering pulls the earthquake signal out of the noise for the Chilean earthquake recorded on KIP Z, E-W, and MAT Z. Outputs 2 through 4/40 show most of the corresponding records. The MAT Z-amplitude of the Rayleigh wave (p-p) after the 40-sec HP filtering was 9.4 digital units (12 mμ, p-p), whereas the noise on the original unfiltered Z was about 90 to 100 digital units (p-p) (see Output 4). Figure 4 presents the same single component data as Figure 3 plus those for the rotated radial horizontal component (R), and the correlation sum traces of either the three components (SM) or the radial and vertical components (RSM) for the optimum HP filter. It is clear (Fig. 4A) that correlation increases as more and more of the long-period noise is filtered out (to 40 sec) until part of the signal becomes filtered out as well, at least for weak signals such as those from the Chile earthquake. The same observation holds for the C:SN (Fig. 4B). Increased correlation results in a smaller standard error for the amplitude determination; increased C:SN, in better detection. It is also seen that the radial component alone gives both higher correlation and better C:SN than either of the horizontal components. In effect, this is the same as polarization filtering. The same improvement also holds for the rotated sum (RSM) trace over the SM trace for KIP. It was not possible to obtain rotated data for MAT since the E-W component was not operating properly. Most of the individual output plots from which the data points were obtained are presented in the output section. It should be stressed that all Rayleigh wave signals were well below the noise level of the original records (Outputs 2, 3, and 4).

If S/N ratio of the original record is defined as (p-p) filtered signal)/(p-p unfiltered noise), all in digital units, then C:SN is the S/N ratio of the processed record; an improvement would be (C:SN)/(S/N original record). Improvement of the normalized matched filter for KIP without HP-filtering on a single trace seems to be near 12 db and at about 16 to 19 db when 40-sec HP-filtering is applied. However, very weak signals (as Z MAT--Chile 40-sec HP) seem to show higher improvement (22 db). This is partially due to the limit on the correlation trace being = 1 (or a C:SN of nearly 5 since noise correlated with the reference signal by about 0.2 or less).

AMPLITUDES AND RELATIVE MAGNITUDES

Figure 5 presents the amplitude (p-p) determinations from the variously filtered outputs. The individual amplitudes are obtained by multiplying the p-p amplitude of the reference earthquake by the relative amplitude (slope) of the scanned earthquake. As an example, consider the vertical component of the Kuril Islands earthquake of October 3 (day 276), 1973 at station MAT (in Output 1). Maximum correlation occurs where the start of the reference signal is positioned at the vertical line (near 13^H01^M). The vertical correlation trace time label is displaced to an earlier time by the difference between the origin time and start time of the reference earthquake Rayleigh-wave trace. The peak occurs at $12^H54^M52^{Sec}$ (printed out as: "time of maximum is: 1973-276-12:54:52" on the right-hand side). This time is the origin time (see table, p. 19). The reference earthquake had a maximum p-p amplitude of 4585 digital units (from the lower edge to the upper edge of the left-hand scale, repeated over the word "station" for clarity). This value multiplied by the relative amplitude of the signal in the scanned trace gives the maximum p-p signal amplitude of the correlated earthquake. The relative amplitude is printed out on the right-hand side under: "Slope is 0.069446". Therefore, the amplitude of the vertical signal for this Kuril Islands earthquake recorded at MAT is 318.4 digital units (with a standard error of ± 4585 • 0.0016987 or ± 7.8 digital units). Note that usually the maximum p-p amplitude on the record (356 digital units near $13^H04^M30^{Sec}$) would be picked to determine the magnitude from this record. The $\log_{10}$ of the relative amplitude ($\log_{10} 0.069446 = - 1.16$) gives the difference in surface-wave magnitude (- 1.16) between the Kuril Islands extracted and reference earthquakes. Similarly, the difference in magnitude at station KIP (see vertical, Output 2) is $\log_{10} 0.071356 = - 1.15$. Figure 6 indicates that the magnitude difference ΔM_s is a stable value at a given station, and that even for the extremely weak signals extracted for the Chilean earthquake the variation is only about 0.1. Since the relative standard error SE(b)/b of the slope b (b = relative amplitude with respect to the reference earthquake) is nothing more than a function of reference data length and the correlation obtained (see Appendix for derivation), a single curve is valid for all correlation outputs with a fixed reference length. Figure 7 gives the standard error in per cent of the amplitude as a function of the correlation and for N = 841 data points (or 840 sec).

The trend in Figure 5 indicates that one can expect to see signals with about 3 digital units p-p at a correlation level of 0.2 or so, a signal that could be useful if properly identified. The identification can have several forms. Such a signal level still would be determined with a standard error in amplitude of less than 20 per cent (Fig. 7). With such low amplitudes of a few digital units, the limits of the recording system might be reached, rather than those of the method. Since the oceanic path signals from the Kuril Islands and the area off the Chile coast show the maximum p-p record amplitude near 30 sec, 3 digital units (≈ 3 1/2 mμ) will place the detection threshold near $M_s(30) = 2.4$ at 100°.

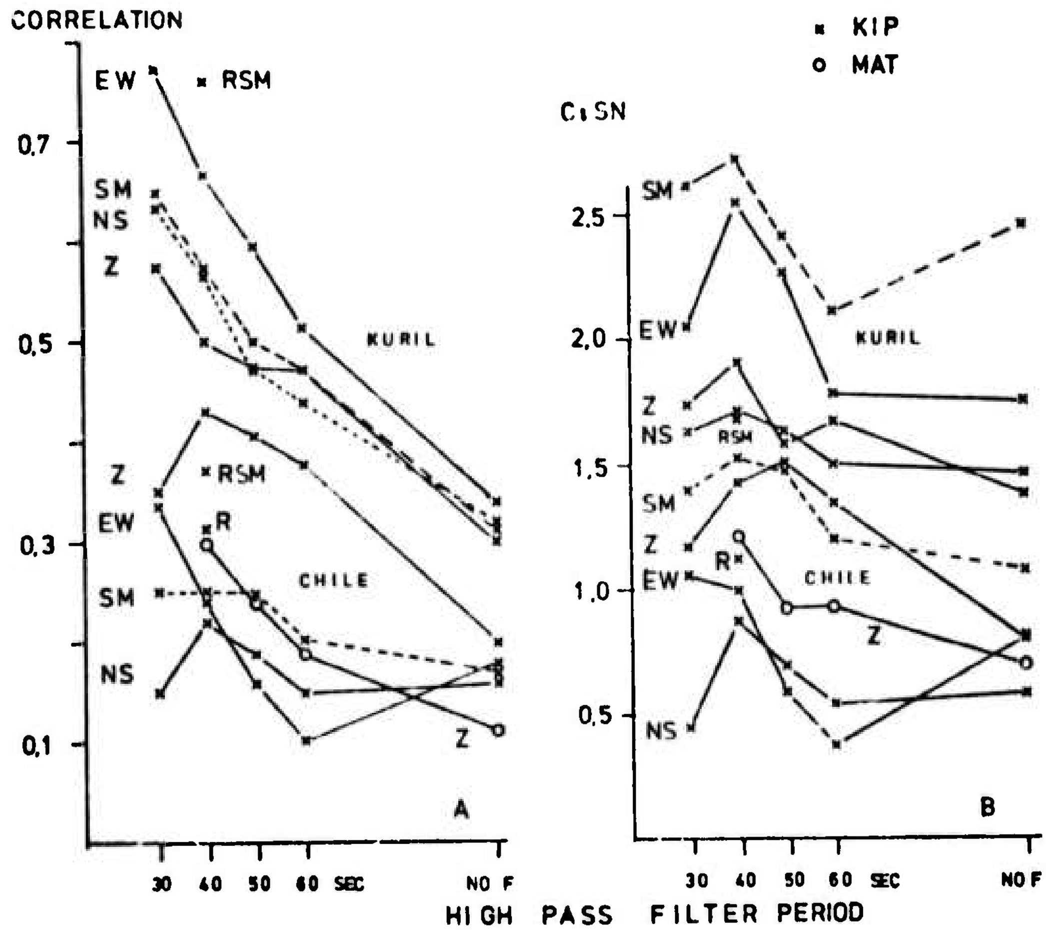

Fig. 4a. Correlation as a function of high pass filter period. Improved correlation results in better signal amplitude determination. SM is one-third the sum of the vertical N-S and E-W component correlation and RSM is one-half the sum of the vertical and radial component correlation. R is the radial component correlation. Note that RSM is a considerable improvement over SM and similarly the correlation of the radial component is better than either E-W or N-S components. Note that C = 0.25 seems to be the correlation where the signal emerges as the highest correlation peak in the half-hour of scanning.

Fig. 4b. Earthquake correlation peak/highest positive correlation noise peak on the half-hour record as function of HP filter period. For C:SN > 1 the earthquake signal is the highest on the half-hour record. The maximum in the signal/noise corresponds to the maximum gain of the instruments and the suppression of noise in the period range beyond 40 sec, where no signal is observed for the pure oceanic path.

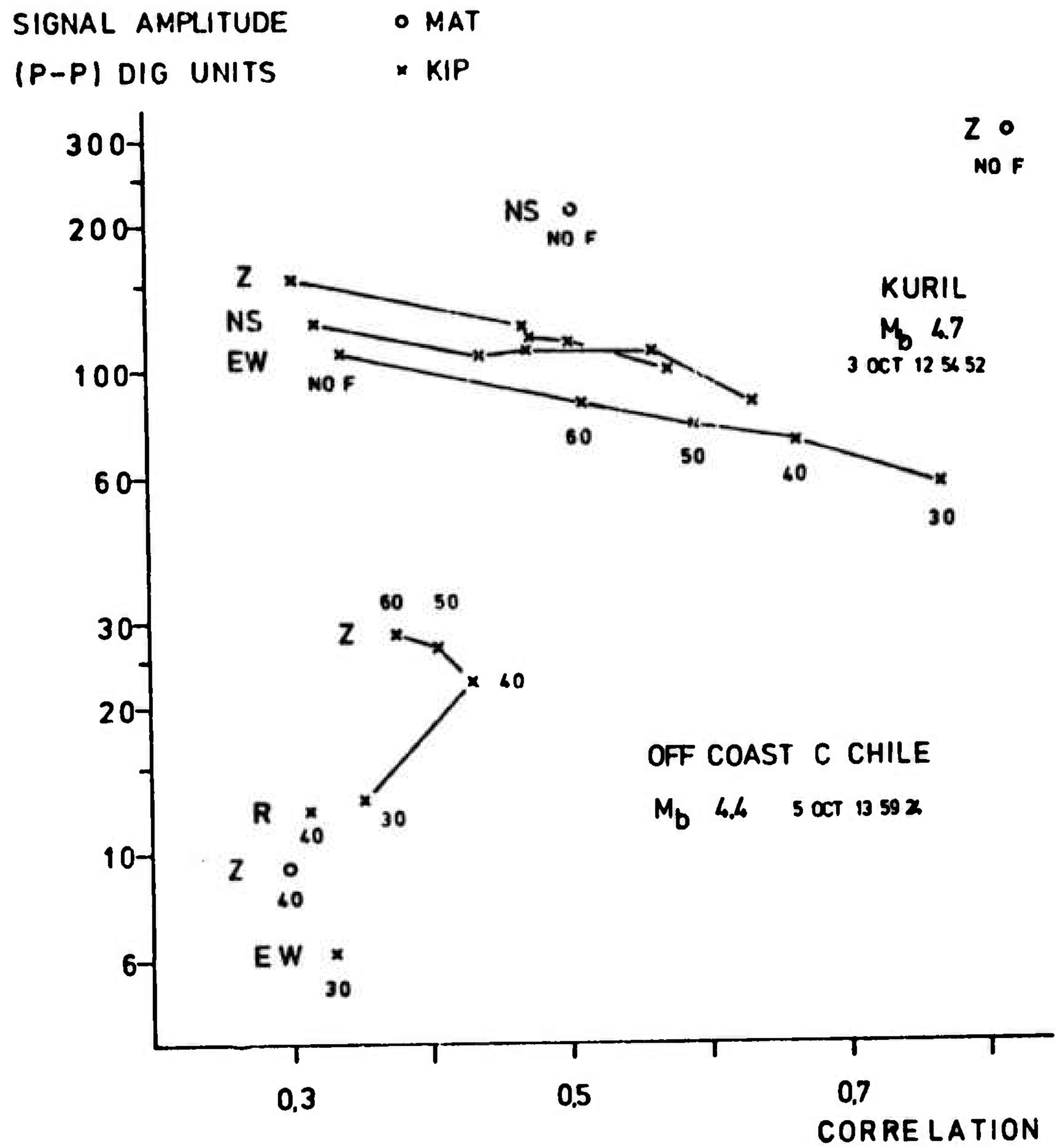

Fig. 5. Signal amplitudes extracted by normalized matched filtering after high pass filtering, at periods indicated, for single component records. In all cases the correlation (positive) peak was the highest during the half-hour scan. Standard error of the amplitudes with a correlation (C) near 0.3 is about 11 per cent and decreases to 6 per cent for C near 0.5.

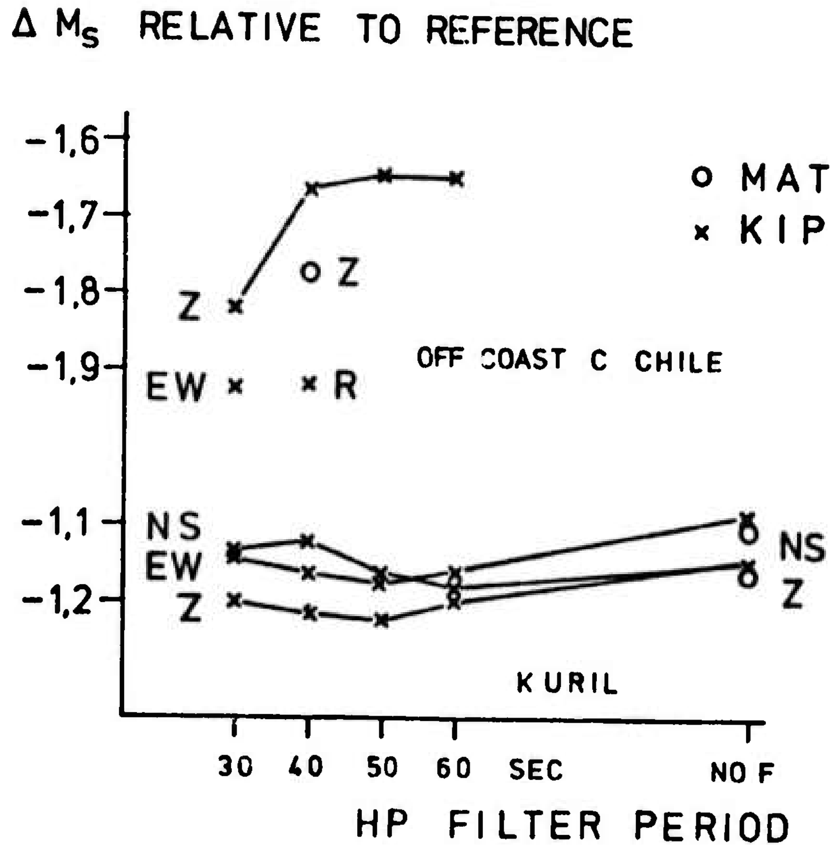

Fig. 6. Difference in surface wave magnitude of extracted signal with respect to reference earthquake. Note the very small variation for various HP filters or between MAT and KIP for the unfiltered records (Kuril Islands earthquake). In all records, signal level was below noise (except MAT-Kuril); in the case of MAT-Z Chile, by as much as a factor near 10.

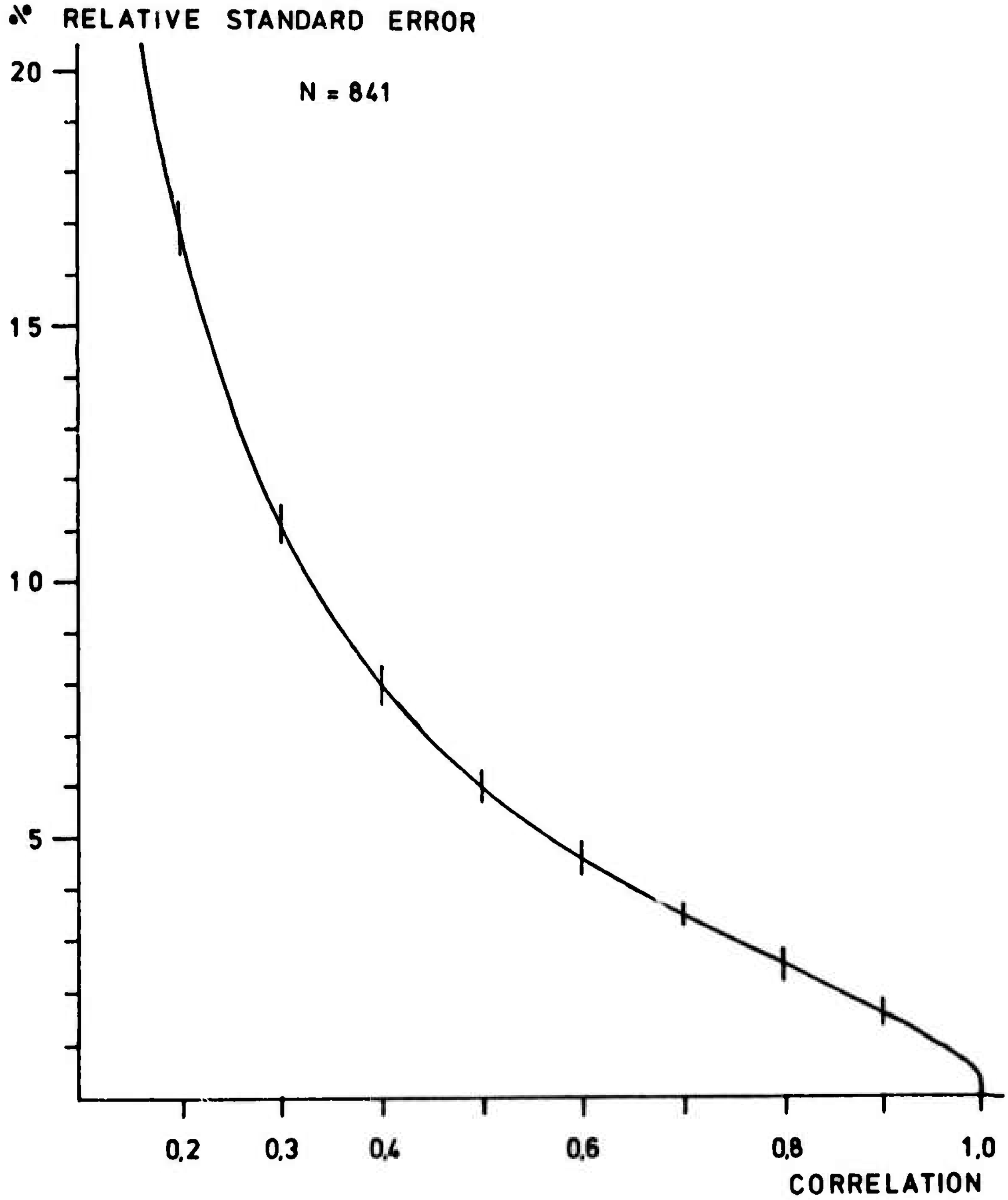

Fig. 7. Relative standard error as a function of correlation coefficient between two data sets, 841 data points each.

SEPARATION OF OVERLAPPING WAVE TRAINS

At a single station the (earthquake reference) matched filter also separates out either co-located events with small time differences, or a widely separated (undesired) event when the Rayleigh wave arrivals are almost simultaneous, or both. The relative amplitudes can be obtained as explained earlier.

Outputs 5, 6, and 7 show the separation of two M_s = 6.5 earthquakes off the coast of Chile that occurred 145 sec and about 0.7° apart. A very clear separation is obtained at KIP (Output 5) and MAT (Output 6) despite the relatively noise-contaminated reference used for MAT. Even the MAT SM correlation trace shows the separation despite the one-third contribution from the non-operating E-W component. Note also that neither rotation nor filtering was applied. Output 7 is the one-half (SM KIP + SM MAT) signal, clearly defining the signals as originating in the area off the coast of Central Chile.

Output 8R shows an example of extraction, at KIP, of a Novaya Zemlya event M_b = 4.8 with negative correlation. An interfering Rayleigh wave arrived about 2 minutes earlier (approximate arrival underlined) from the Kermadec Islands (M_b = 5.0). Since an explosion was used as a reference trace, the negative correlation clearly indicates that the later event was not an explosion but rather an earthquake or a cavity collapse. Note that the interfering Rayleigh wave (from the S-W of KIP) has a dispersed Z component correlation that is quite different from the negative correlated signal, and that the SM trace nearly eliminates this undesirable signal. SM presents nearly the rotated SM output, since the signal from Novaya Zemlya arrived approximately from the north.

Finally, Output 9 shows the original data for two earthquakes from off the coast of central Chile (M_b = 4.4 and 4.5), separated by 6 minutes. Interfering Rayleigh waves from two Central Alaska earthquakes arrived 15 minutes before the first one and just between the two (approximate arrival time underlined on Output 9/40R, the HP-filtered and rotated record for these same earthquakes). The computer correctly picked one of them on the vertical and the other on the radial trace. Signal peaks on the RSM trace are clearly the highest during the processed time interval.

Table of Earthquakes (USGS Monthly Listings, October 1973)

Day	Time	Coordinate			Depth, km	M_b	M_s	Remarks	Output nos.
3	10 35 51.2	45.5N	151.8E	Kuril Is.	N	5.2	4.8	Reference earthquake	
3	12 54 52.3	45.7N	151.7E		N	4.7		Scanned, data length, various filters	1, 2-2/30
5	05 45 27.3	33.0S	71.9W	Off coast C-Chile	14	5.8	6.5	) Separate	5, 6, 7
5	05 47 51.1*	32.5S	71.5W		N	5.8	6.7	)	
5	08 57 21.7	32.9S	72.0W		N	4.6			
5	09 12 17.5	33.2S	72.1W		N	4.5		) Extract and separate) from preceding and the) two following earth-quakes	9, 9/40R
5	09 18 26.2	33.1S	72.1W		N	4.4			
5	09 22 06.3*	66.3N	157.4W	Alaska	68	4.1			
5	09 40 39.8	66.2N	157.3W	Alaska	42				
5	13 59 24.0*	33.0S	72.2W	Off coast C-Chile	N	4.4		Extract, various fil-ters, rotation	3-3/30, 4, 4/40
6	04 24 49.5	33.1S	72.1W		21	5.0		Reference earthquake	
27	06 59 57.4	70.8N	54.2E	Novaya Zemlya	0 G	6.9	5.5	Reference, explosion	
27	09 13 51.3*	71.3N	51.9E	Novaya Zemlya	0 G	4.8		Extract and separate from following earth-quake	8, 8/40R
27	09 25 46.1*	33.7S	179.4E	S of Kermadec Is.	N	5.0			

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APPENDIX

"O" Phase-Shift High Pass Filter

If $A(j)$ is the original data trace $j = 1,2...$

digitized at a time interval Δt,

the filtered output $AF(j)$ is given by:

$$AF(j) = \sum_{i=1}^{2N+1} A(j-1-N+i) \cdot F(i)$$

and $F(i) = T(i) \cdot W(i)$

where $T(i)$ = tapering function

$W(i)$ = Fourier transform of the frequency window.

The Hamming tapering function is:

$$T(i) = 0.54 + 0.46 \cos\left[\frac{(-N-1+i)\pi\Delta t}{N\Delta t}\right]$$

and $W(i)$ for a high pass filter is:

$$W(i) = \delta\,(N+1-i) - 2\Delta t f_H \cdot \frac{\sin\left[(-N-1+i)\pi 2\Delta t f_H\right]}{(-N-1+i)\pi 2\Delta t f_H}$$

2N+1 = total filter length

$i = 1,2\ldots 2N+1$

$\delta(x) = 0$ for $x \neq 0$

$= 1$ for $x = 0$

f_H = high pass corner frequency .

Rotation

The rotation program is applied to either the direct data or the filtered data. Only a fixed average gain factor is used; however, at present the gain factor is variable with frequency.

A_1 = amplitude of Z component in digital units

A_2 = amplitude of N-S component in digital units

A_3 = amplitude of E-W component in digital units.

If φ = angle at station clockwise from North to epicenter, the transformation is given by:

$$A_1 = A_1$$

$$R = G_3A_3 \sin \varphi + A_2 \cos \varphi \qquad \text{(radial)}$$

$$T = G_3A_3 (- \cos \varphi) + A_2 \sin \varphi \qquad \text{(transverse)}.$$

The gain factor G_3 is set so that, as an average over the predominant frequency range,

$$G_3 = \frac{A_2 \text{(digital units/}\mu\text{ of calibration}}{A_3 \text{(digital units/}\mu\text{ of calibration}} .$$

The transformation gives the output R, T in digital units, approximately at the gain of component A_2(N-S) with R positive towards the epicenter.

Correlation

The cross correlation (normalized matched filtering) between a reference earthquake and a scanned record is performed either for

(a) the direct data as recorded and for each individual channel (Z, N-S, E-W);

(b) the high-pass filtered data with the same filter applied to the reference earthquake and the scanned data first; or

(c) the rotated (or rotated and filtered) data and for the channels Z, AR, AT.

The following gives the cross correlation for a single component (as under a, b, or c (Δt = 1 sec being omitted from the formulas)):

$R(i) = R(t_{RB}-1+i)$ reference time series $i = 1,2,\ldots N$

$N = t_{RE} - t_{RB} + 1$ $\qquad$ t_{RB} = beginning time of reference

t_{RE} = end time of reference.

$S(j) = S(t_E-1+j)$ = scanned time series

$j = 1,2,\ldots,t_E-t_S+1$ $\qquad$ t_S = start time of scan

t_E = end time of scan

$S(t)$ is required from $t = t_S$ to $t = t_E + N$.

The correlation output is

$C(j) = C(t) = C(t_S - 1 + j - (t_{RB} - t_{RO}))$

t_{RO} = origin time of reference earthquake (from bulletins, and so forth)

$$C(t) = \frac{N\sum_{i=1}^{N} R(i)\, S(t_S-1+j+i) - \sum_{i=1}^{N} R(i) \cdot \sum_{i=1}^{N} S(t_S-1+j+i)}{\left[N\sum_{i=1}^{N} R^2(i) - (\sum_{i=1}^{N} R(i))^2 \right]^{\frac{1}{2}} \left[N\sum_{i=1}^{N} S^2(t_S-1+j+i) - (\sum_{i=1}^{N} S(t_S-1+j+i))^2 \right]^{\frac{1}{2}}}$$

$$j = 1,2,\ldots(t_E-t_S+1)$$

$$= \frac{I}{\sqrt{II}\quad\sqrt{III}}$$

Standard Error

The slope of the regression line of the scanned data $S(j+i)$ on the reference data $R(i)$ is given by:

$$b(t) = \text{slope } (j) = \frac{I}{II},$$

and the standard error of $b(t)$ is:

$$SE(b) = \left[\frac{1}{N-2} \left(\frac{III}{II} - b^2(t) \right) \right]^{\frac{1}{2}}$$

In the present program, the computer retains and prints out the value of b and its standard error only for the time of maximum correlation. The slope is then the relative amplitude of the extracted earthquake with respect to the reference earthquake if the former was correctly picked.

Since $\frac{b^2}{C^2} = \frac{I^2}{II^2} \cdot \frac{II \cdot III}{I^2} = \frac{III}{II}$ $\qquad SE(b) = \left[\frac{1}{N-2} \left(\frac{b^2}{C^2} - b^2 \right) \right]^{\frac{1}{2}}$

or the relative standard error of b

$$\frac{SE(b)}{b} = \left[\frac{1}{N-2} \cdot \left(\frac{1}{C^2} - 1 \right) \right]^{\frac{1}{2}}$$

is only a function of reference data length and the correlation obtained.

Explanation of Output Plots

Output numbers are for reference in text and table of earthquakes. The same number is used for the same station - scanned earthquake combination. A number (60, 50, 40, or 30) after a virgule (/) indicates HP-filtered data at that particular period for both the reference earthquake and the scanned record; R indicates rotated data for the horizontal components.

Trace designation A_1, A_2, A_3: original or HP filtered Z, N-S, E-W; C_1, C_2, C_3: correlation of A_1 with A_1 reference, and so forth; SM: (sum of C traces)/(number of correlation traces), R, CR: radial, radial correlation.

Start time is given after station identification. Tick marks are 2 minutes apart. Amplitudes--(on the left) in digital units (not readable); p-p in digital units, was redrawn over the word "STATION" in most records.

Output # 1, 2, 2R, 2/60, 2/50, 2/40, 2/30	Kuril Islands
3, 3/60, 3/50, 3/40, 3/40R, 3/30 4, 4/40	Off the coast of Central Chile, extraction
5, 6, 7	Off the coast of Central Chile, separation
8R	Novaya Zemlya, extraction, separation
9, 9/40R	Off the coast of Central Chile, extraction and separation. M_b = 4.5 and 4.4

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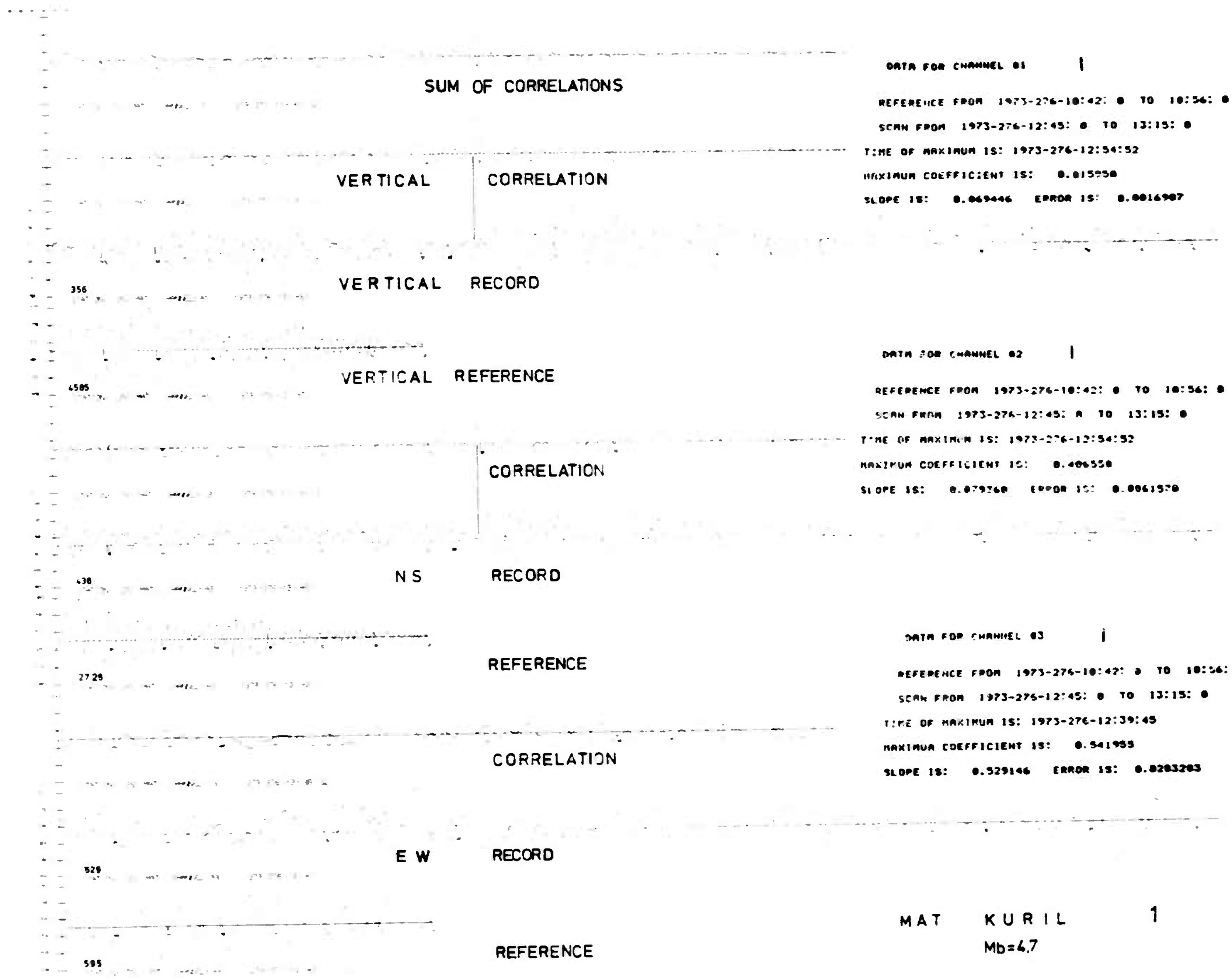


DATA FOR CHANNEL 01 |

REFERENCE FROM 1973-276-10:42: 0 TO 10:56: 0
SCAN FROM 1973-276-12:45: 0 TO 13:15: 0
TIME OF MAXIMUM IS: 1973-276-12:54:52
MAXIMUM COEFFICIENT IS: 0.815950
SLOPE IS: 0.069446 ERROR IS: 0.0016907

DATA FOR CHANNEL 02 |

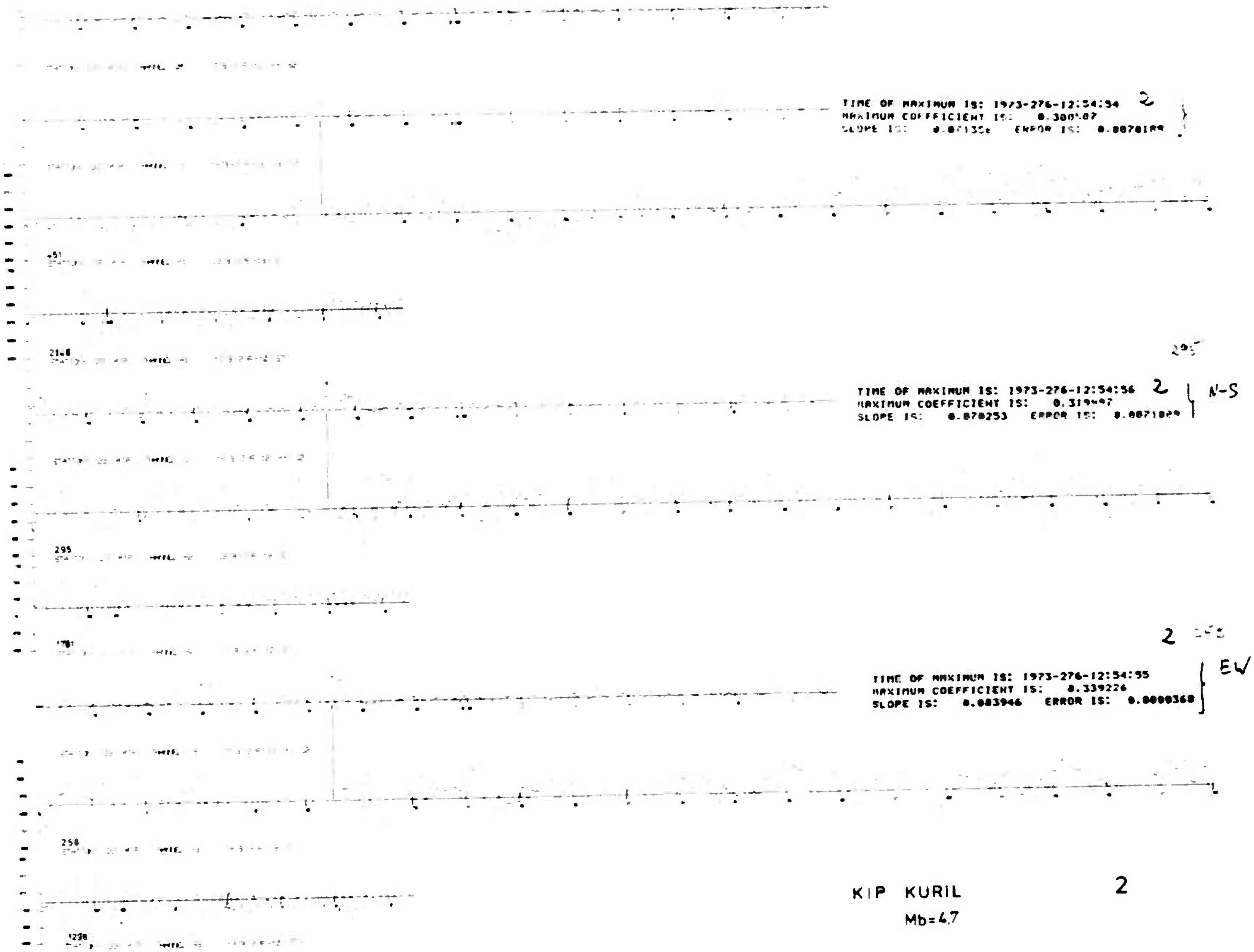
REFERENCE FROM 1973-276-10:42: 0 TO 10:56: 0
SCAN FROM 1973-276-12:45: 0 TO 13:15: 0
TIME OF MAXIMUM IS: 1973-276-12:54:52
MAXIMUM COEFFICIENT IS: 0.406550
SLOPE IS: 0.079360 ERROR IS: 0.0061570

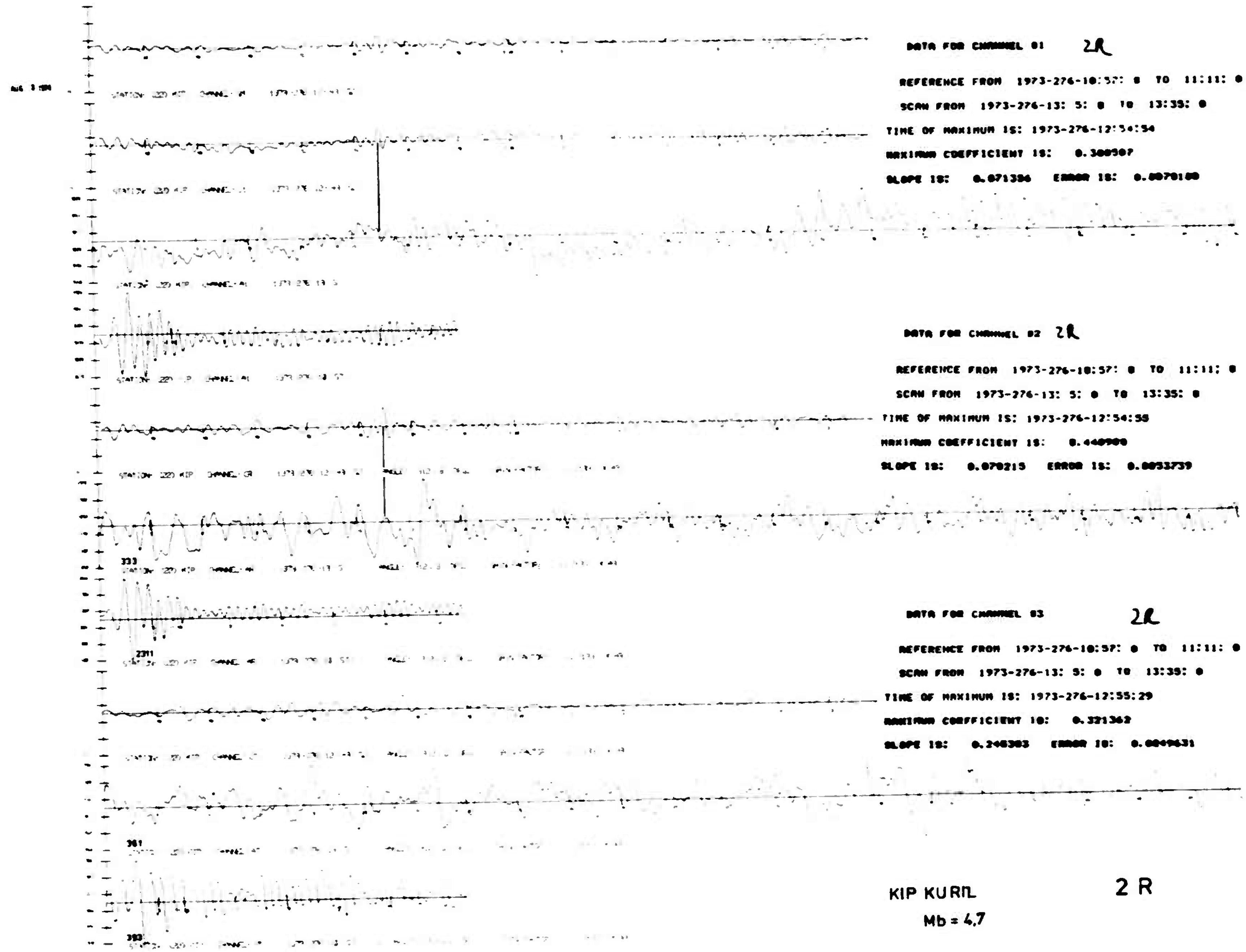
DATA FOR CHANNEL 03 |

REFERENCE FROM 1973-276-10:42: 0 TO 10:56: 0
SCAN FROM 1973-276-12:45: 0 TO 13:15: 0
TIME OF MAXIMUM IS: 1973-276-12:39:45
MAXIMUM COEFFICIENT IS: 0.541955
SLOPE IS: 0.529146 ERROR IS: 0.0203203

MAT KURIL 1

Mb=4.7


TIME OF MAXIMUM IS: 1973-276-12:54:54 2
MAXIMUM COEFFICIENT IS: 0.300407
SLOPE IS: 0.071358 ERROR IS: 0.0070189
451
214
TIME OF MAXIMUM IS: 1973-276-12:54:56 2 N-S
MAXIMUM COEFFICIENT IS: 0.319497
SLOPE IS: 0.070253 ERROR IS: 0.0071089
295
2
TIME OF MAXIMUM IS: 1973-276-12:54:55 EW
MAXIMUM COEFFICIENT IS: 0.339226
SLOPE IS: 0.083946 ERROR IS: 0.0000368
258
1238
KIP KURIL 2
Mb=4.7


DATA FOR CHANNEL 01 2R
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SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:54:54
MAXIMUM COEFFICIENT IS: 0.300507
SLOPE IS: 0.071336 ERROR IS: 0.0070180
DATA FOR CHANNEL 02 2R
REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:54:58
MAXIMUM COEFFICIENT IS: 0.440900
SLOPE IS: 0.070215 ERROR IS: 0.0053739
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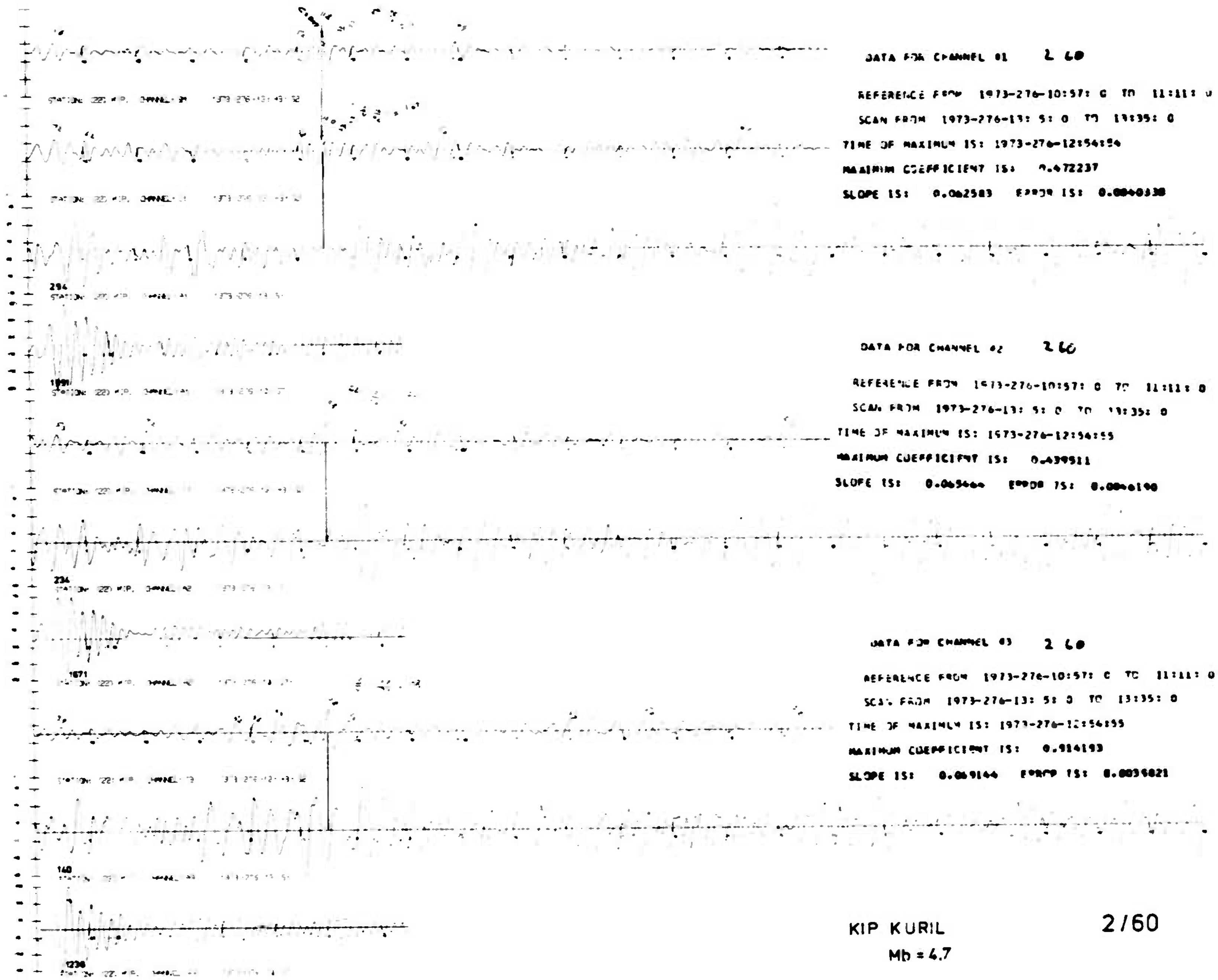
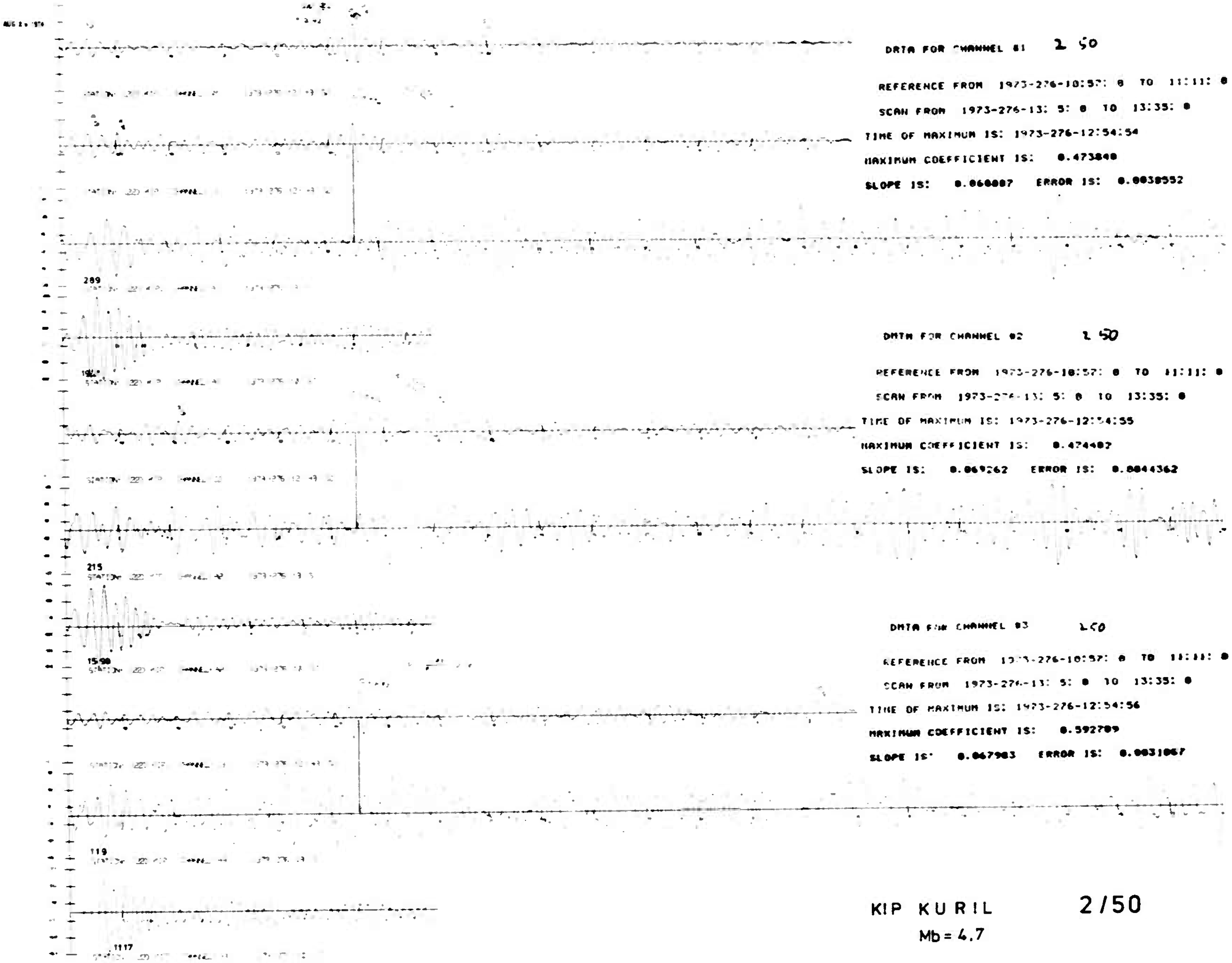
REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:55:29
MAXIMUM COEFFICIENT IS: 0.321362
SLOPE IS: 0.246383 ERROR IS: 0.0049631
KIP KURIL
Mb = 4.7
2 R



KIP KURIL 2/60

Mb = 4.7



DATA FOR CHANNEL #1 2 50

REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:54:54
MAXIMUM COEFFICIENT IS: 0.473840
SLOPE IS: 0.060087 ERROR IS: 0.0038552

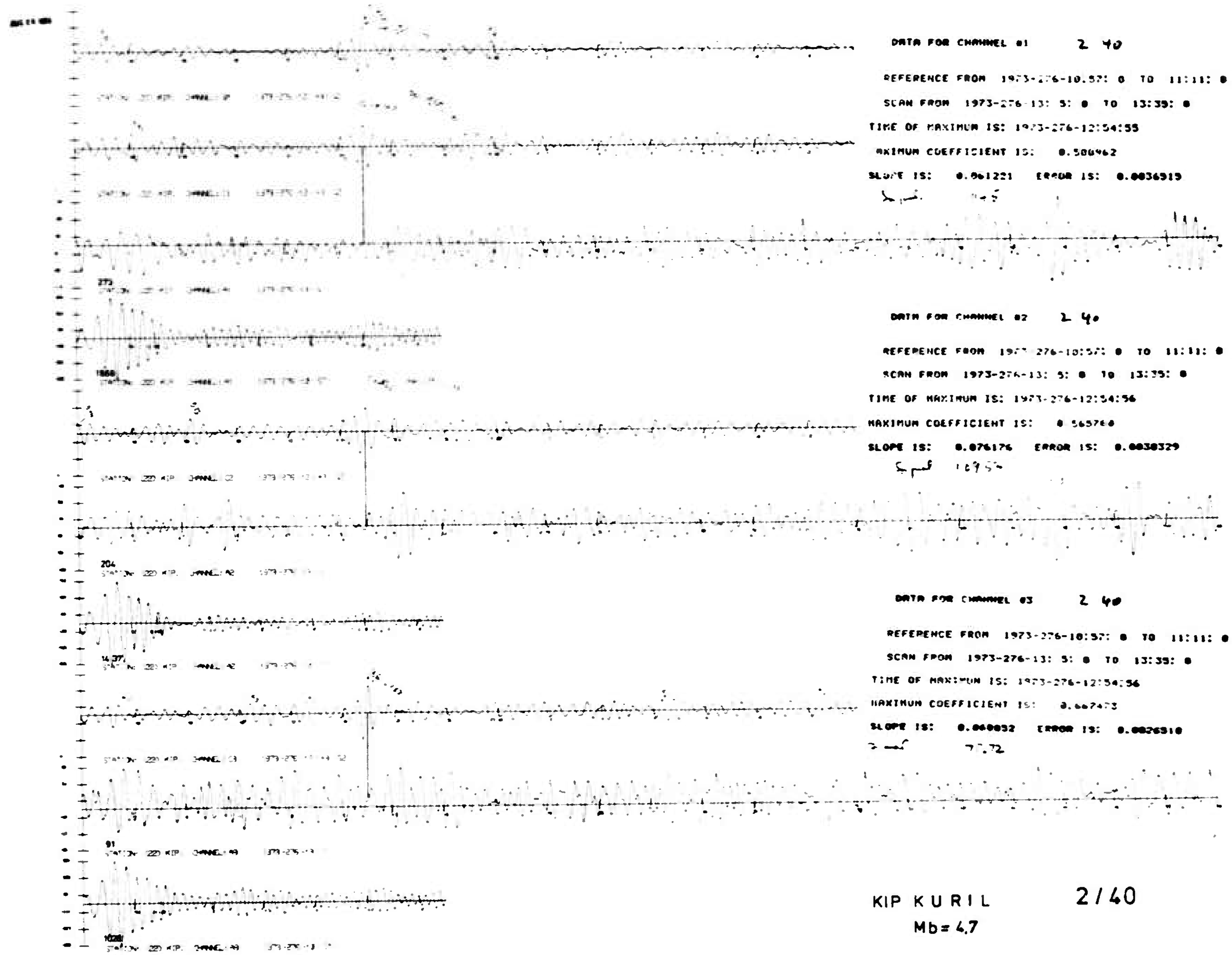
DATA FOR CHANNEL #2 2 50

REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:54:55
MAXIMUM COEFFICIENT IS: 0.474482
SLOPE IS: 0.069262 ERROR IS: 0.0044362

DATA FOR CHANNEL #3 2 50

REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:54:56
MAXIMUM COEFFICIENT IS: 0.592709
SLOPE IS: 0.067983 ERROR IS: 0.0031067

KIP KURIL 2/50
Mb = 4.7



DATA FOR CHANNEL 01   2 40

REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:39: 0
TIME OF MAXIMUM IS: 1973-276-12:54:55
MAXIMUM COEFFICIENT IS: 0.506962
SLOPE IS: 0.061221 ERROR IS: 0.0036915

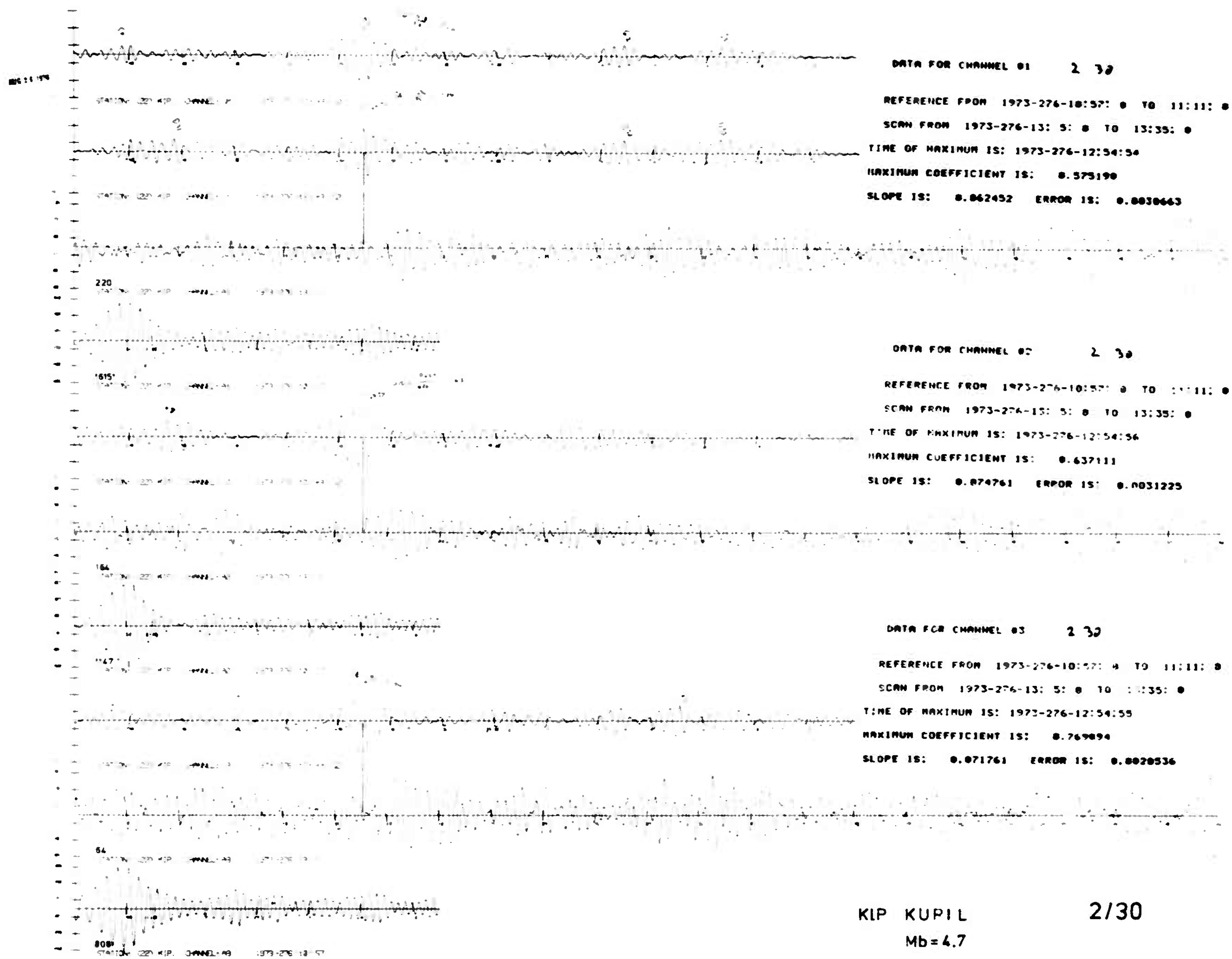
DATA FOR CHANNEL 02   2 40

REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:54:56
MAXIMUM COEFFICIENT IS: 0.565764
SLOPE IS: 0.076176 ERROR IS: 0.0038329

DATA FOR CHANNEL 03   2 40

REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:39: 0
TIME OF MAXIMUM IS: 1973-276-12:54:56
MAXIMUM COEFFICIENT IS: 0.667473
SLOPE IS: 0.060052 ERROR IS: 0.0026510

KIP KURIL   2/40
Mb= 4.7


DATA FOR CHANNEL 01 2 30
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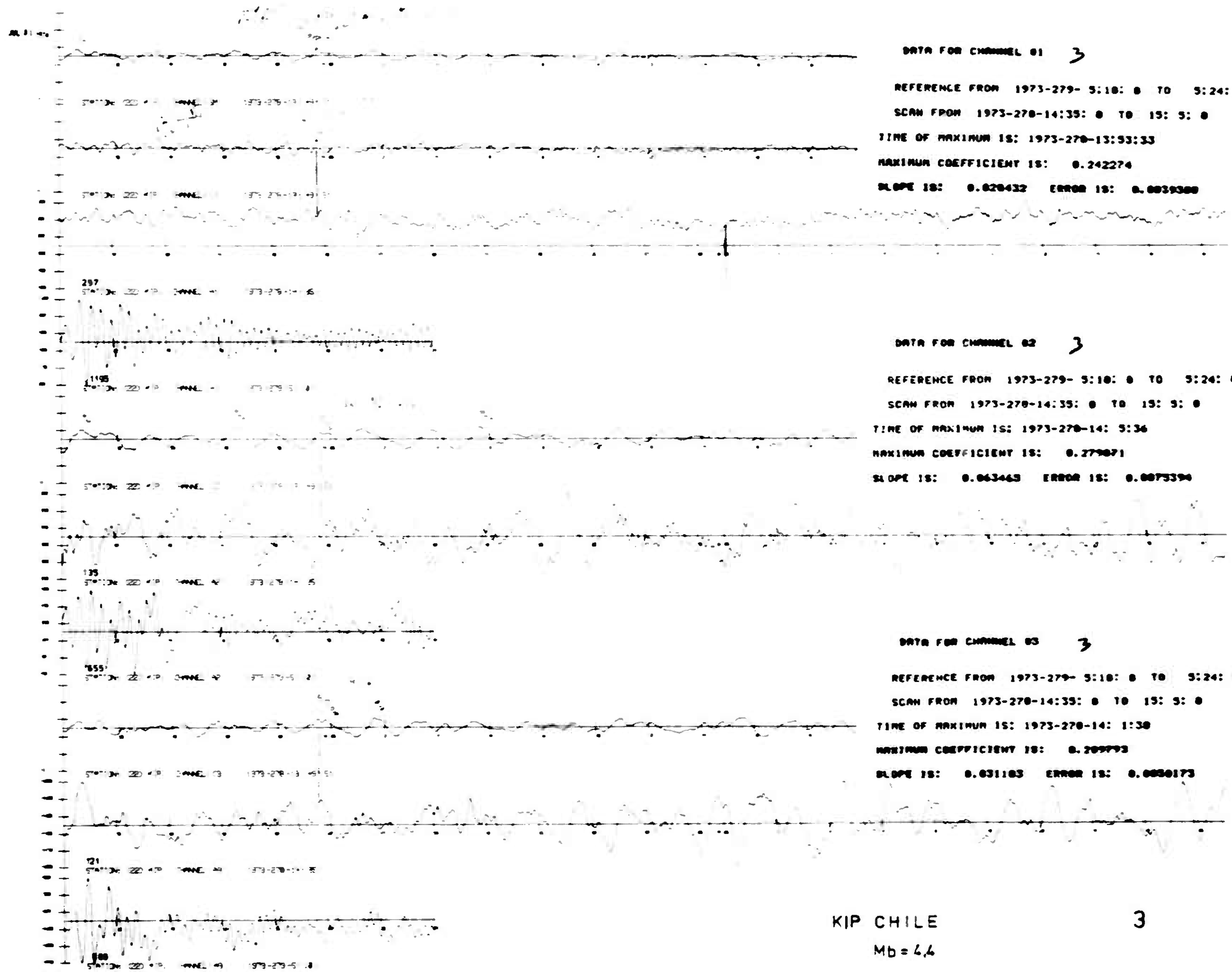
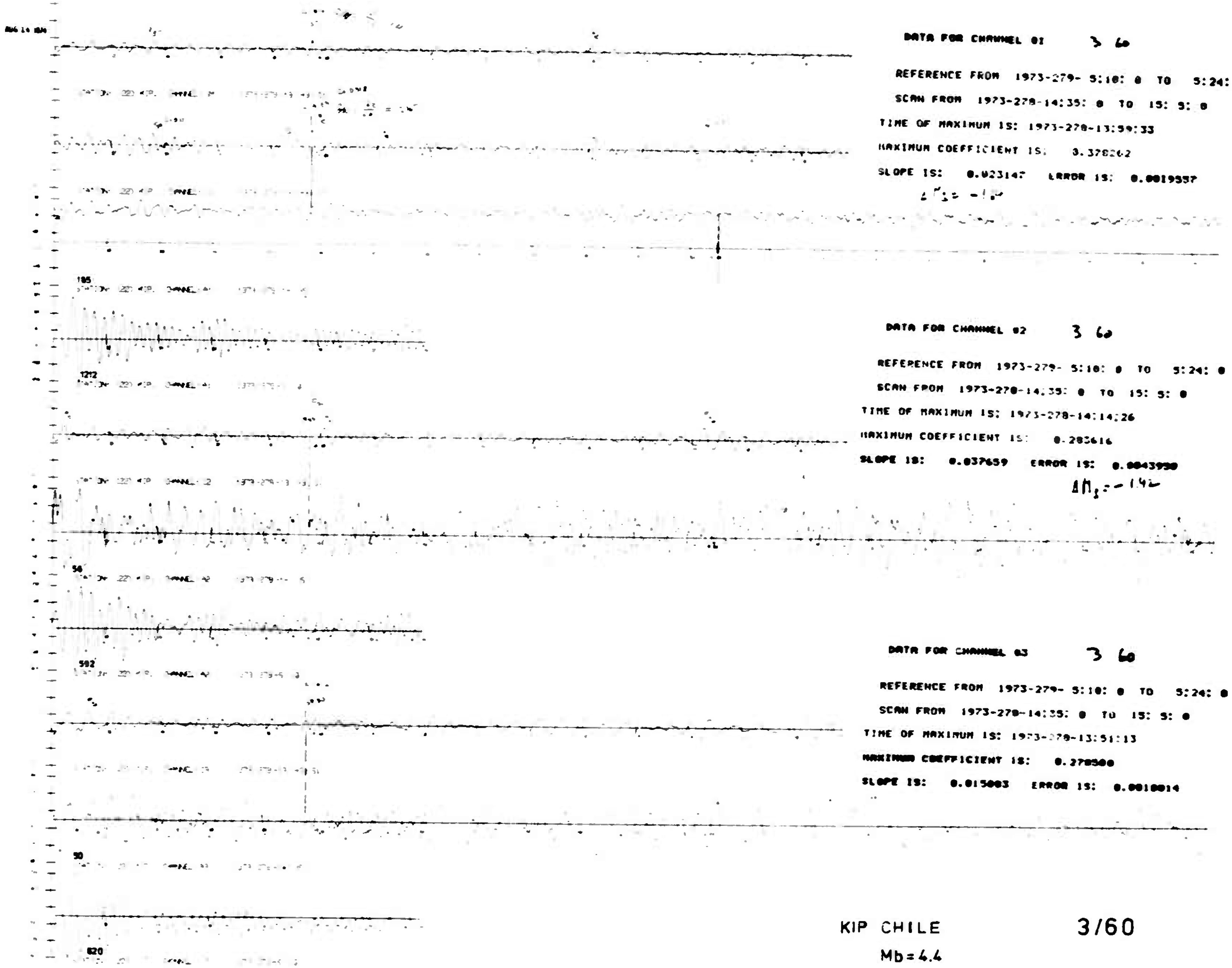
SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:54:54
MAXIMUM COEFFICIENT IS: 0.575190
SLOPE IS: 0.062452 ERROR IS: 0.0030663
DATA FOR CHANNEL 02 2 30
REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:54:56
MAXIMUM COEFFICIENT IS: 0.637111
SLOPE IS: 0.074761 ERROR IS: 0.0031225
DATA FOR CHANNEL 03 2 30
REFERENCE FROM 1973-276-10:57: 0 TO 11:11: 0
SCAN FROM 1973-276-13: 5: 0 TO 13:35: 0
TIME OF MAXIMUM IS: 1973-276-12:54:55
MAXIMUM COEFFICIENT IS: 0.769094
SLOPE IS: 0.071761 ERROR IS: 0.0020536
220
164
64
KIP KUPIL
Mb=4.7
2/30



KIP CHILE 3

Mb = 4.4



DATA FOR CHANNEL 01 3 6

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0

SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0

TIME OF MAXIMUM IS: 1973-278-13:59:33

MAXIMUM COEFFICIENT IS: 3.378262

SLOPE IS: 0.023147 ERROR IS: 0.0019557

$\Delta M_s = -1.6$

DATA FOR CHANNEL 02 3 6

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0

SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0

TIME OF MAXIMUM IS: 1973-278-14:14:26

MAXIMUM COEFFICIENT IS: 0.283616

SLOPE IS: 0.037659 ERROR IS: 0.0043930

$\Delta M_s = -1.42$

DATA FOR CHANNEL 03 3 6

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0

SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0

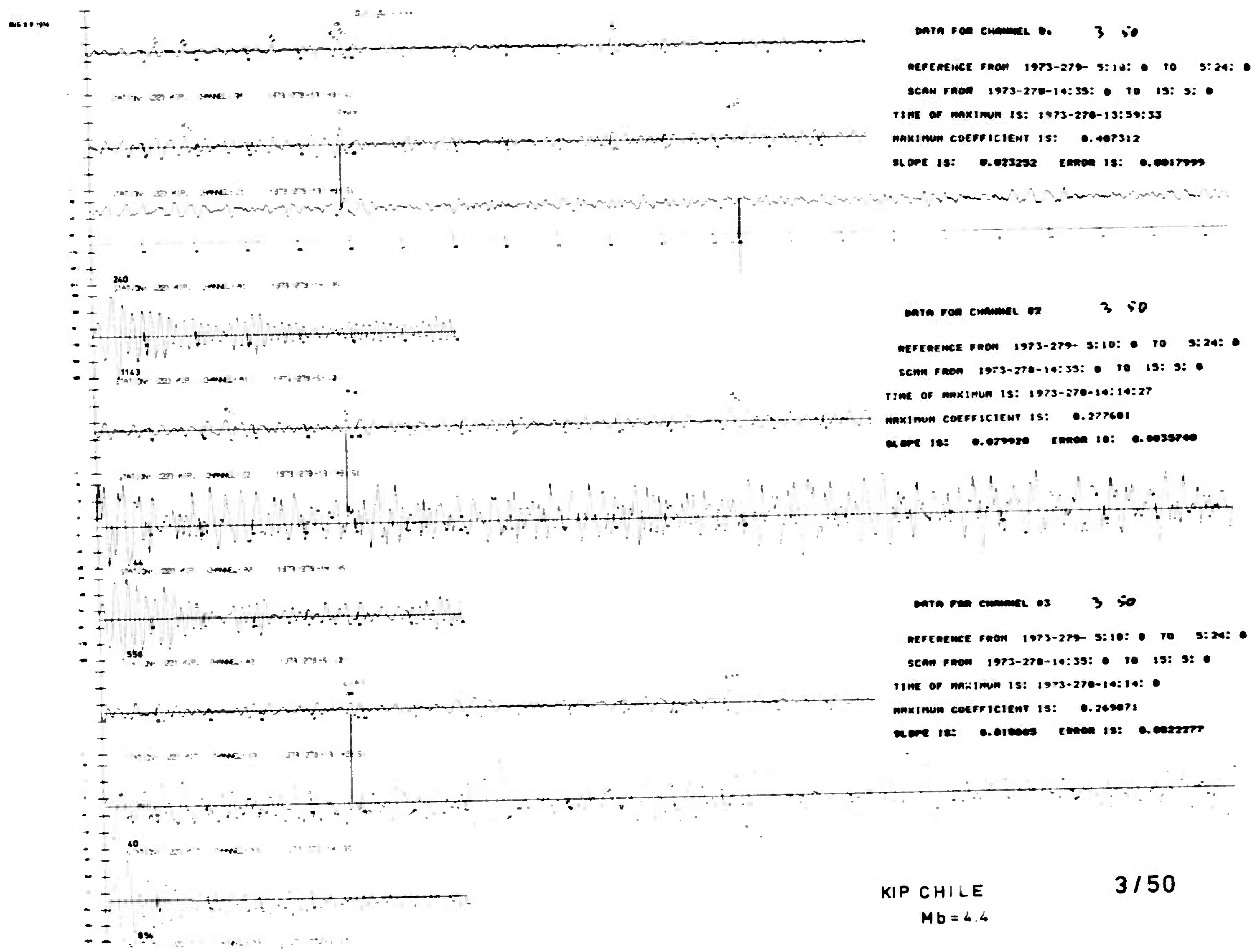
TIME OF MAXIMUM IS: 1973-278-13:51:13

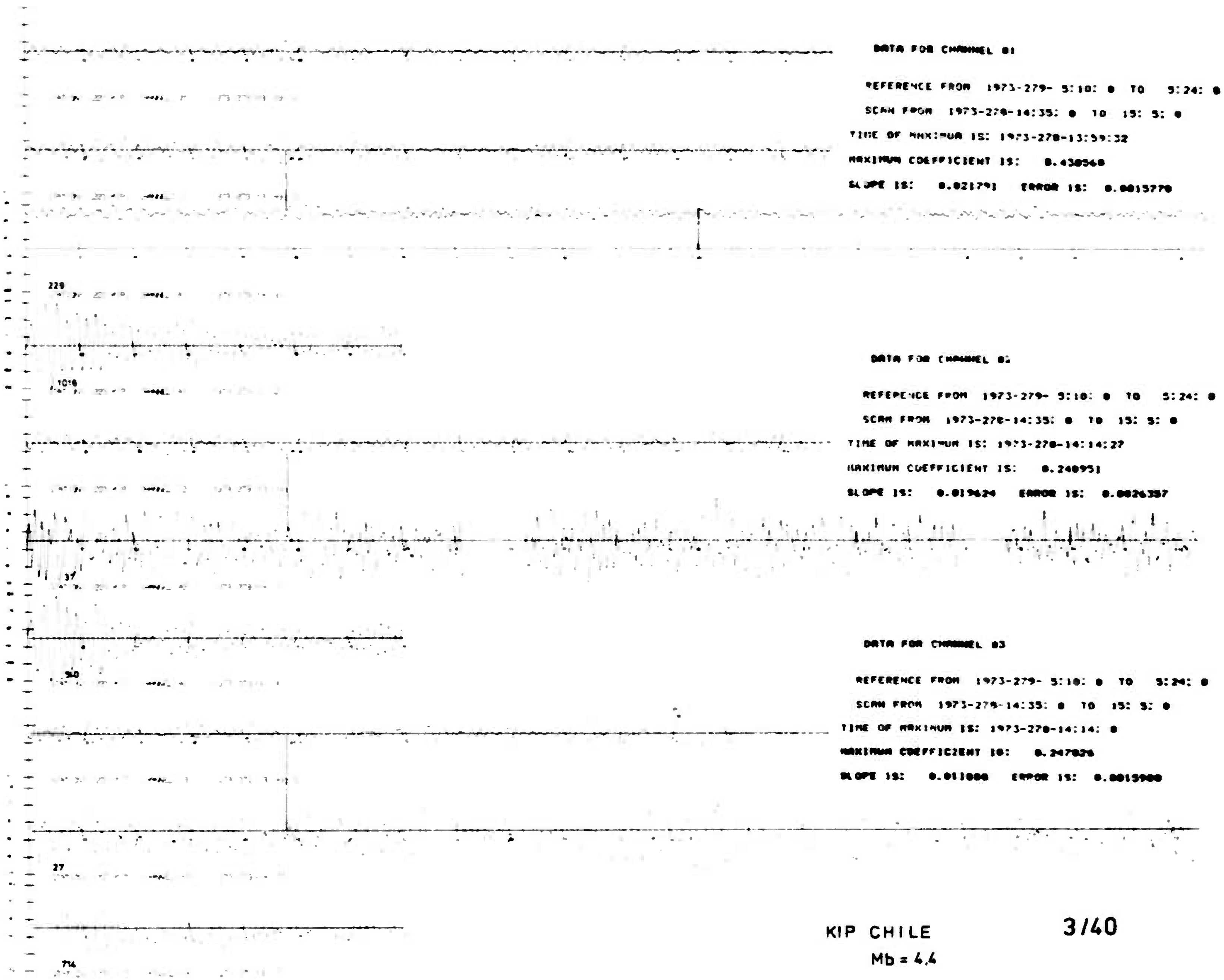
MAXIMUM COEFFICIENT IS: 0.278500

SLOPE IS: 0.015003 ERROR IS: 0.0018014

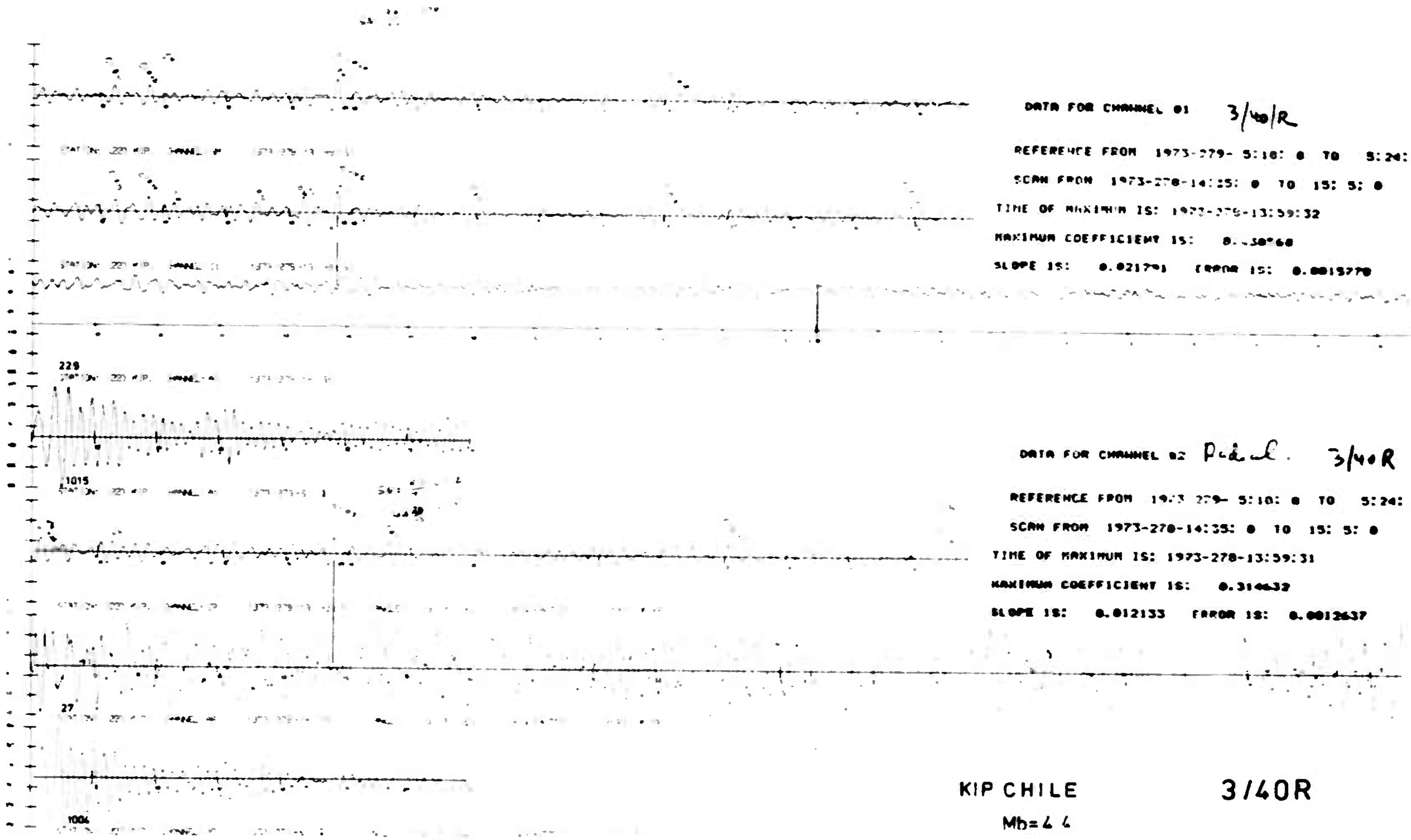
KIP CHILE 3/60

Mb=4.4


DATA FOR CHANNEL 0. 3 50
REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0
SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0
TIME OF MAXIMUM IS: 1973-278-13:59:33
MAXIMUM COEFFICIENT IS: 0.407312
SLOPE IS: 0.023252 ERROR IS: 0.0017999
DATA FOR CHANNEL 02 3 50
REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0
SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0
TIME OF MAXIMUM IS: 1973-278-14:14:27
MAXIMUM COEFFICIENT IS: 0.277601
SLOPE IS: 0.079920 ERROR IS: 0.0035740
DATA FOR CHANNEL 03 3 50
REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0
SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0
TIME OF MAXIMUM IS: 1973-278-14:14: 0
MAXIMUM COEFFICIENT IS: 0.269871
SLOPE IS: 0.010005 ERROR IS: 0.0022277
240
1143
44
556
40
856
KIP CHILE
Mb=4.4
3/50



KIP CHILE 3/40
Mb = 4.4



DATA FOR CHANNEL 01 3/40/R

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0

SCAN FROM 1973-278-14:25: 0 TO 15: 5: 0

TIME OF MAXIMUM IS: 1973-278-13:59:32

MAXIMUM COEFFICIENT IS: 0.-30*60

SLOPE IS: 0.021791 ERROR IS: 0.0015770

DATA FOR CHANNEL 02 P.d. L. 3/40R

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0

SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0

TIME OF MAXIMUM IS: 1973-278-13:59:31

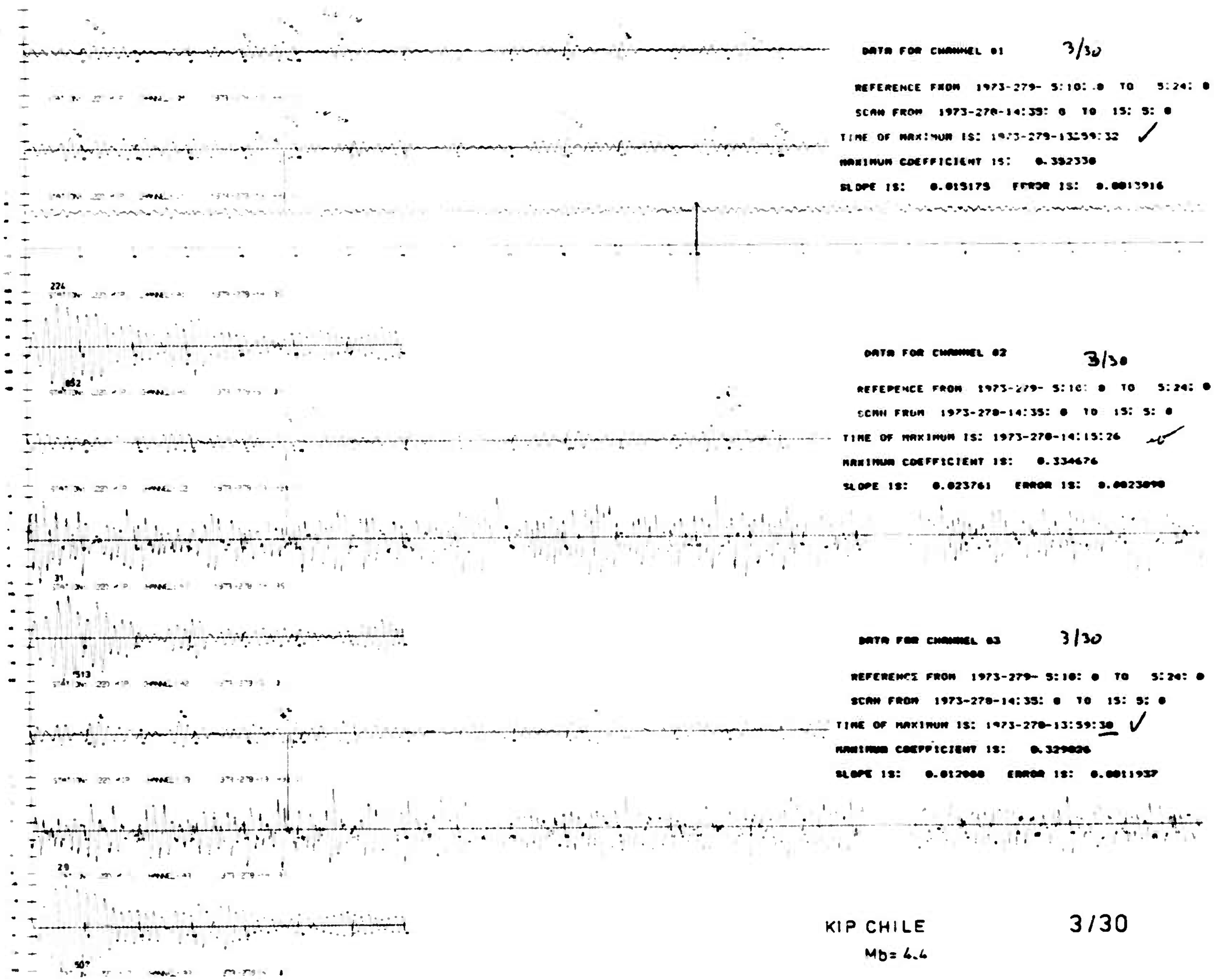
MAXIMUM COEFFICIENT IS: 0.314632

SLOPE IS: 0.012133 ERROR IS: 0.0012637

KIP CHILE

Mb=4.4

3/40R



DATA FOR CHANNEL 01 3/30

REFERENCE FROM 1973-279- 5:10: .0 TO 5:24: 0

SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0

TIME OF MAXIMUM IS: 1973-279-13:59:32 ✓

MAXIMUM COEFFICIENT IS: 0.392330

SLOPE IS: 0.015175 ERROR IS: 0.0013916

DATA FOR CHANNEL 02 3/30

REFEPENCE FROM 1973-279- 5:10: 0 TO 5:24: 0

SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0

TIME OF MAXIMUM IS: 1973-278-14:15:26

MAXIMUM COEFFICIENT IS: 0.334676

SLOPE IS: 0.023761 ERROR IS: 0.0023090

DATA FOR CHANNEL 03 3/30

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0

SCAN FROM 1973-278-14:35: 0 TO 15: 5: 0

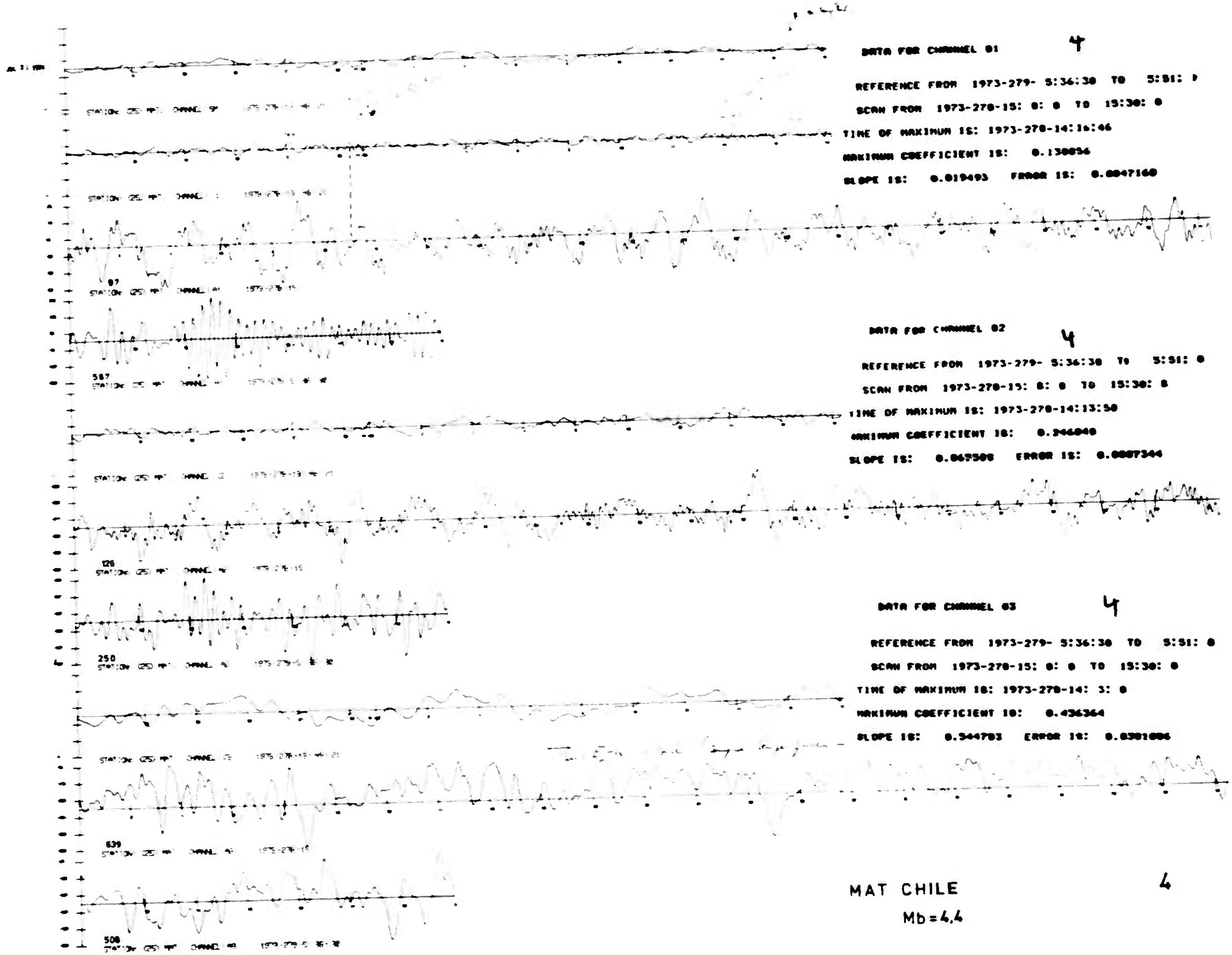
TIME OF MAXIMUM IS: 1973-278-13:59:30 ✓

MAXIMUM COEFFICIENT IS: 0.329026

SLOPE IS: 0.012060 ERROR IS: 0.0011937

KIP CHILE 3/30

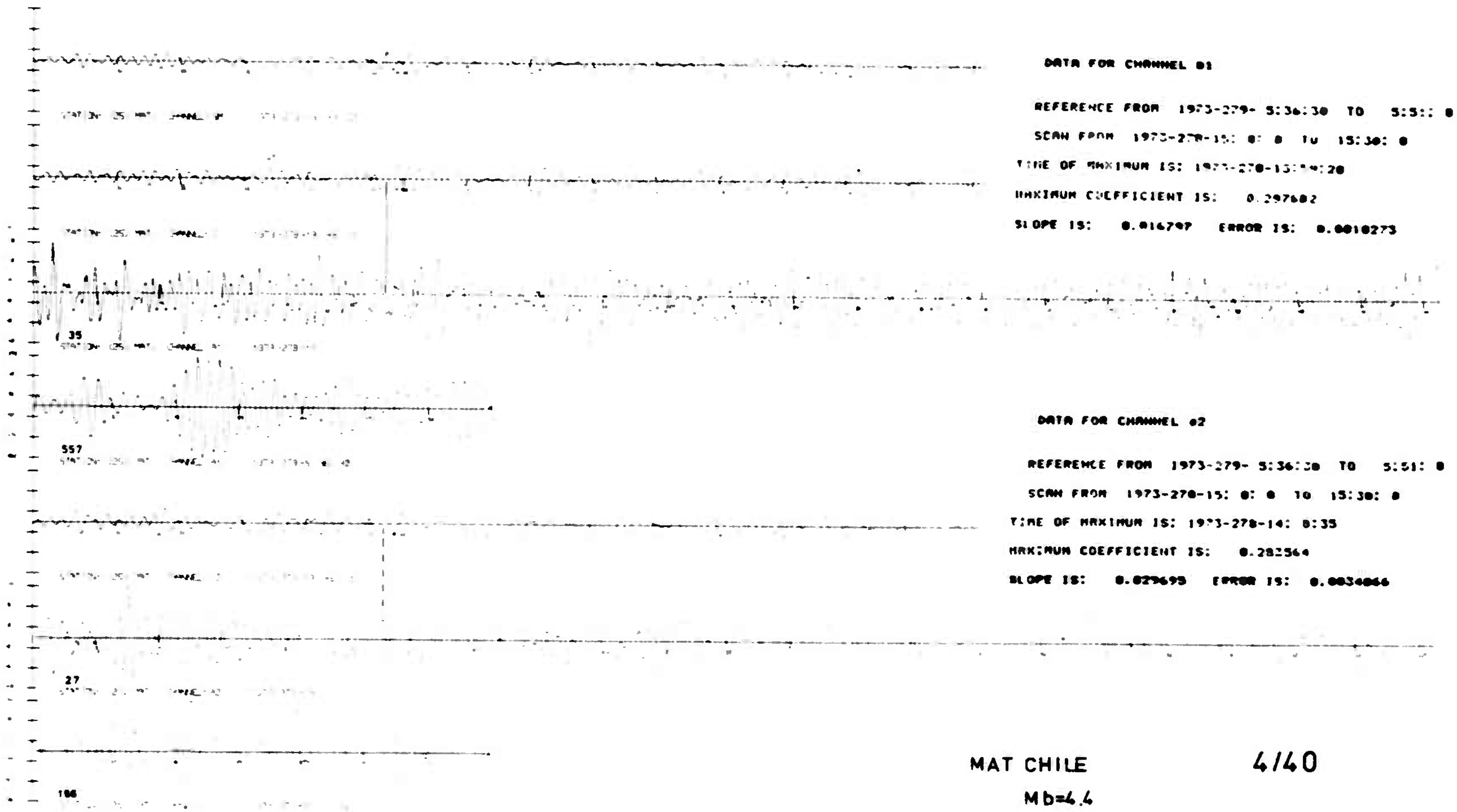
Mb= 4.4



MAT CHILE

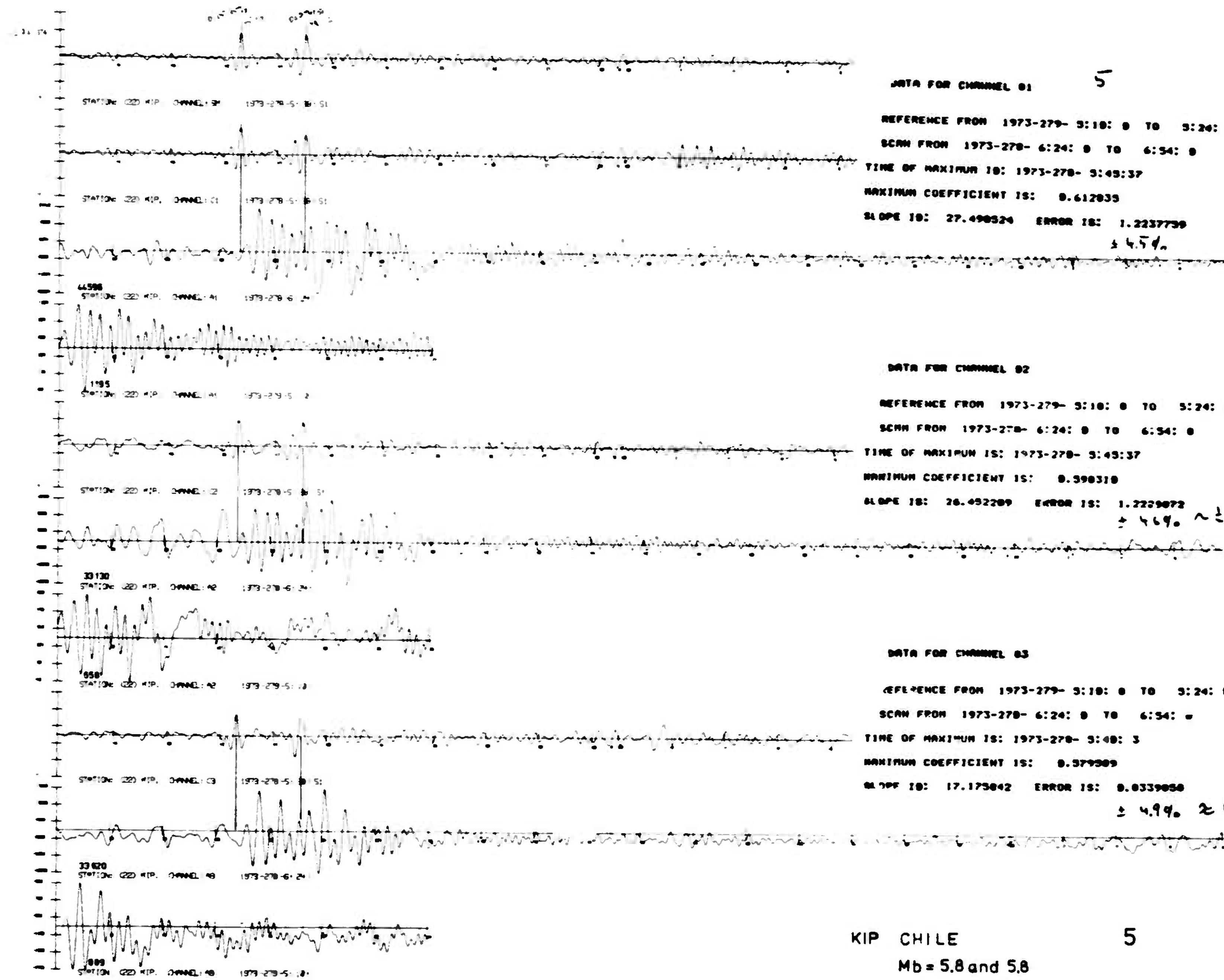
Mb=4.4

4



MAT CHILE 4/40

Mb=4.4



DATA FOR CHANNEL 01 5

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0

SCAN FROM 1973-278- 6:24: 0 TO 6:54: 0

TIME OF MAXIMUM IS: 1973-278- 5:45:37

MAXIMUM COEFFICIENT IS: 0.612035

SLOPE IS: 27.490524 ERROR IS: 1.2237730

± 4.5%

DATA FOR CHANNEL 02 5

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0

SCAN FROM 1973-278- 6:24: 0 TO 6:54: 0

TIME OF MAXIMUM IS: 1973-278- 5:45:37

MAXIMUM COEFFICIENT IS: 0.590310

SLOPE IS: 26.452209 ERROR IS: 1.2229072

± 4.6% ~ ± 1/6

DATA FOR CHANNEL 03

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0 5

SCAN FROM 1973-278- 6:24: 0 TO 6:54: 0

TIME OF MAXIMUM IS: 1973-278- 5:40: 3

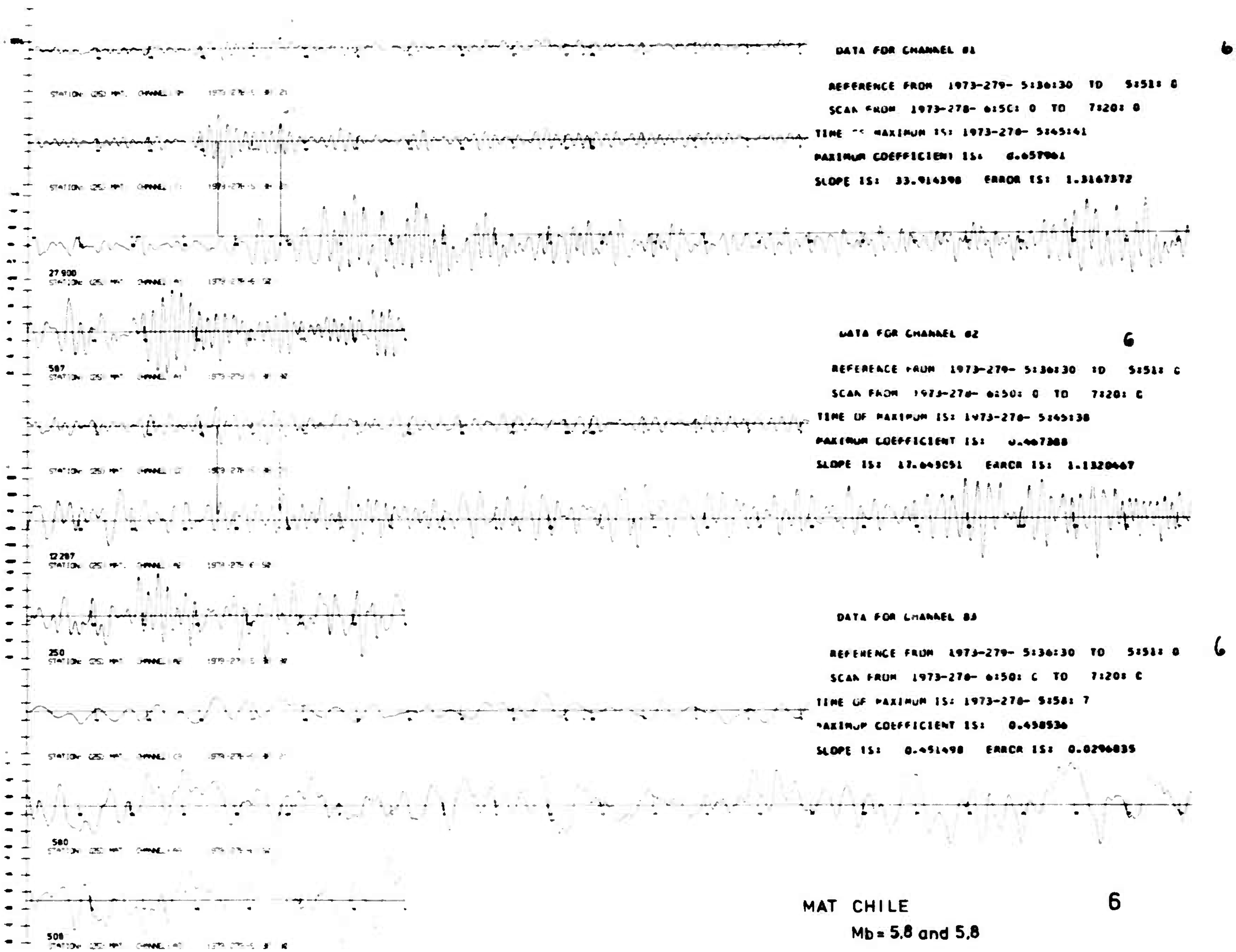
MAXIMUM COEFFICIENT IS: 0.579509

SLOPE IS: 17.175042 ERROR IS: 0.8539050

± 4.9% ≈ 0.5 db

KIP CHILE 5

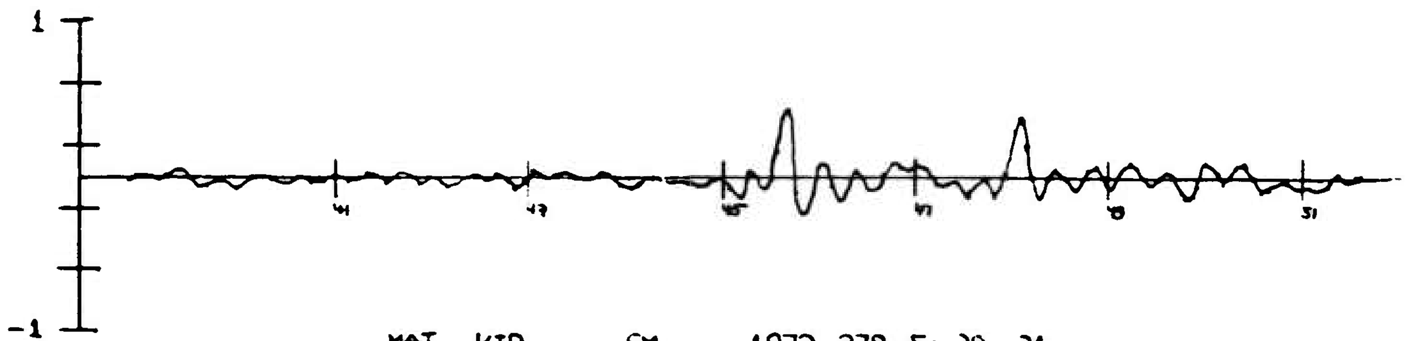
Mb = 5.8 and 5.8



MAT CHILE

Mb = 5.8 and 5.8

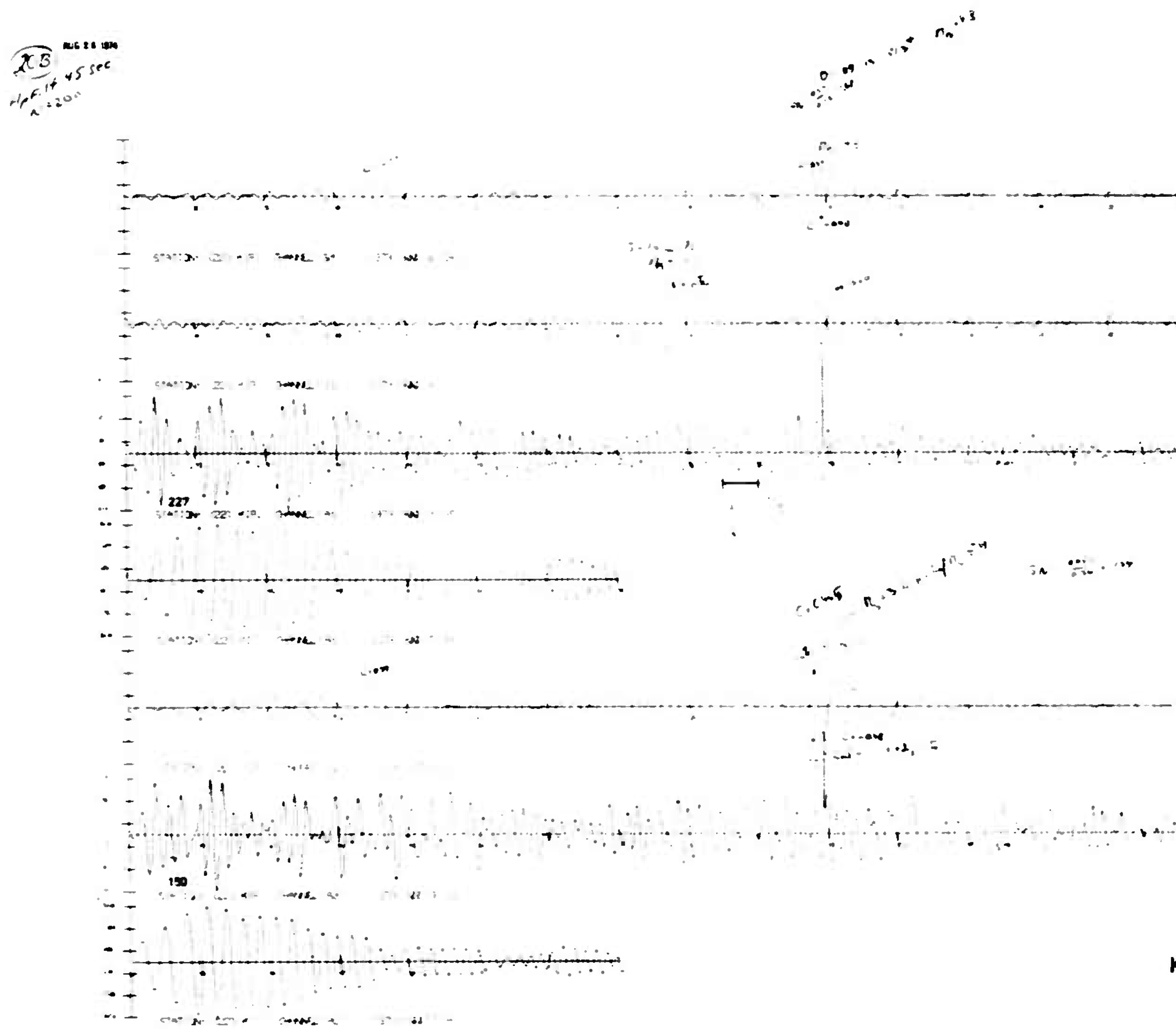
6



MAT. KIP. SM 1973-278-5: 38: 21

CHILE Mb= 5.8 and 5.8

7



DATA FOR CHANNEL 01

REFERENCE FROM 1973-300- 7:41: 0 TO 7:55: 0

SCAN FROM 1973-300- 9:35: 0 TO 10: 5: 0

TIME OF MAXIMUM IS: 1973-300- 9: 9:36

MAXIMUM COEFFICIENT IS: 0.529689

SLOPE IS: 0.009432 ERROR IS: 0.0005269

8R

DATA FOR CHANNEL 02

REFERENCE FROM 1973-300- 7:41: 0 TO 7:55: 0

SCAN FROM 1973-300- 9:35: 0 TO 10: 5: 0

TIME OF MAXIMUM IS: 1973-300- 9:13:37

MAXIMUM COEFFICIENT IS: 0.454564

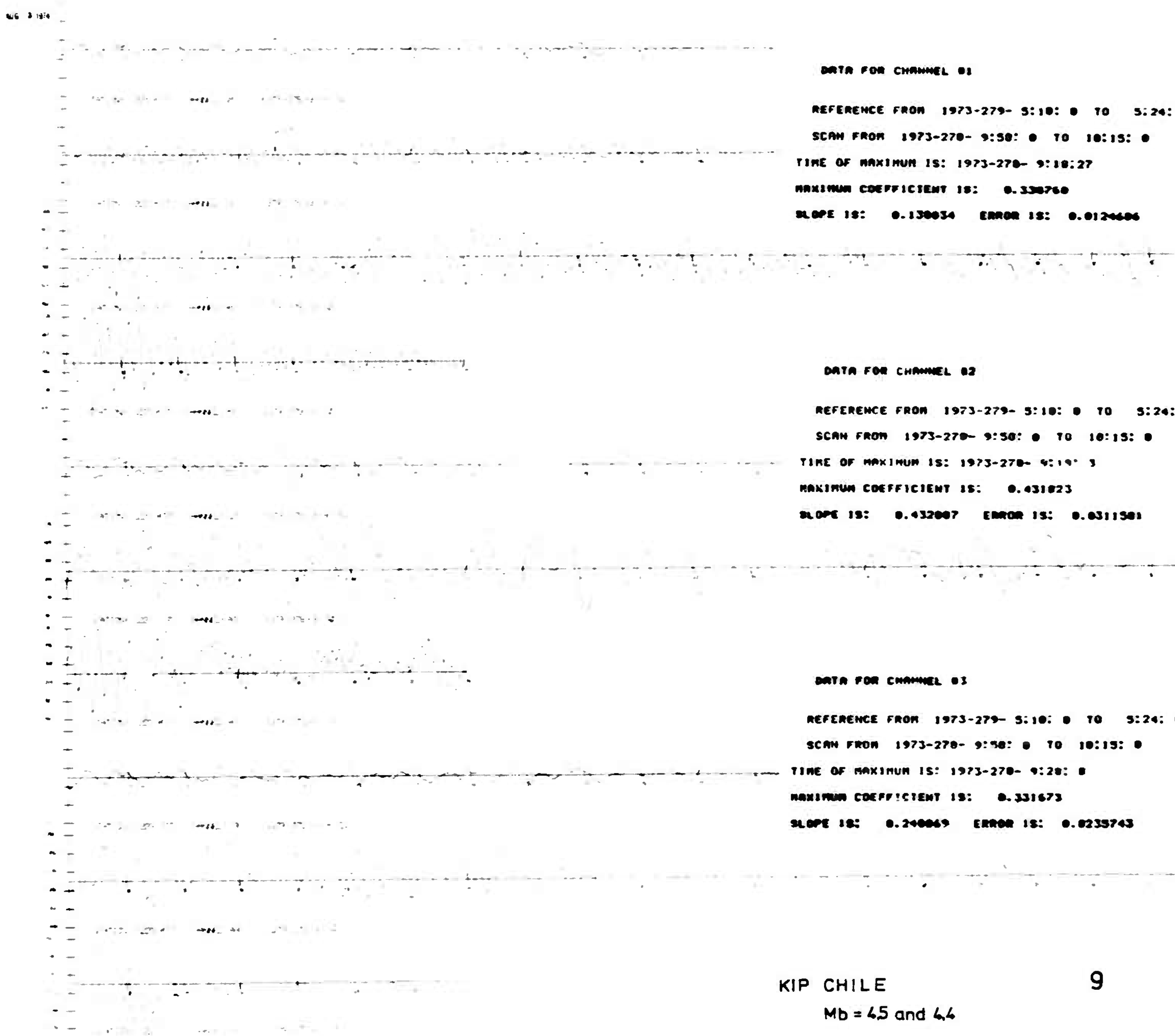
SLOPE IS: 0.006695 ERROR IS: 0.000452

8R

M_s =

KIP NOVAYA Z. 8R

Mb 4.8



DATA FOR CHANNEL 01

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0
SCAN FROM 1973-270- 9:50: 0 TO 10:15: 0
TIME OF MAXIMUM IS: 1973-270- 9:18:27
MAXIMUM COEFFICIENT IS: 0.338760
SLOPE IS: 0.130034 ERROR IS: 0.0124606

DATA FOR CHANNEL 02

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0
SCAN FROM 1973-270- 9:50: 0 TO 10:15: 0
TIME OF MAXIMUM IS: 1973-270- 9:19: 3
MAXIMUM COEFFICIENT IS: 0.431023
SLOPE IS: 0.432007 ERROR IS: 0.0311501

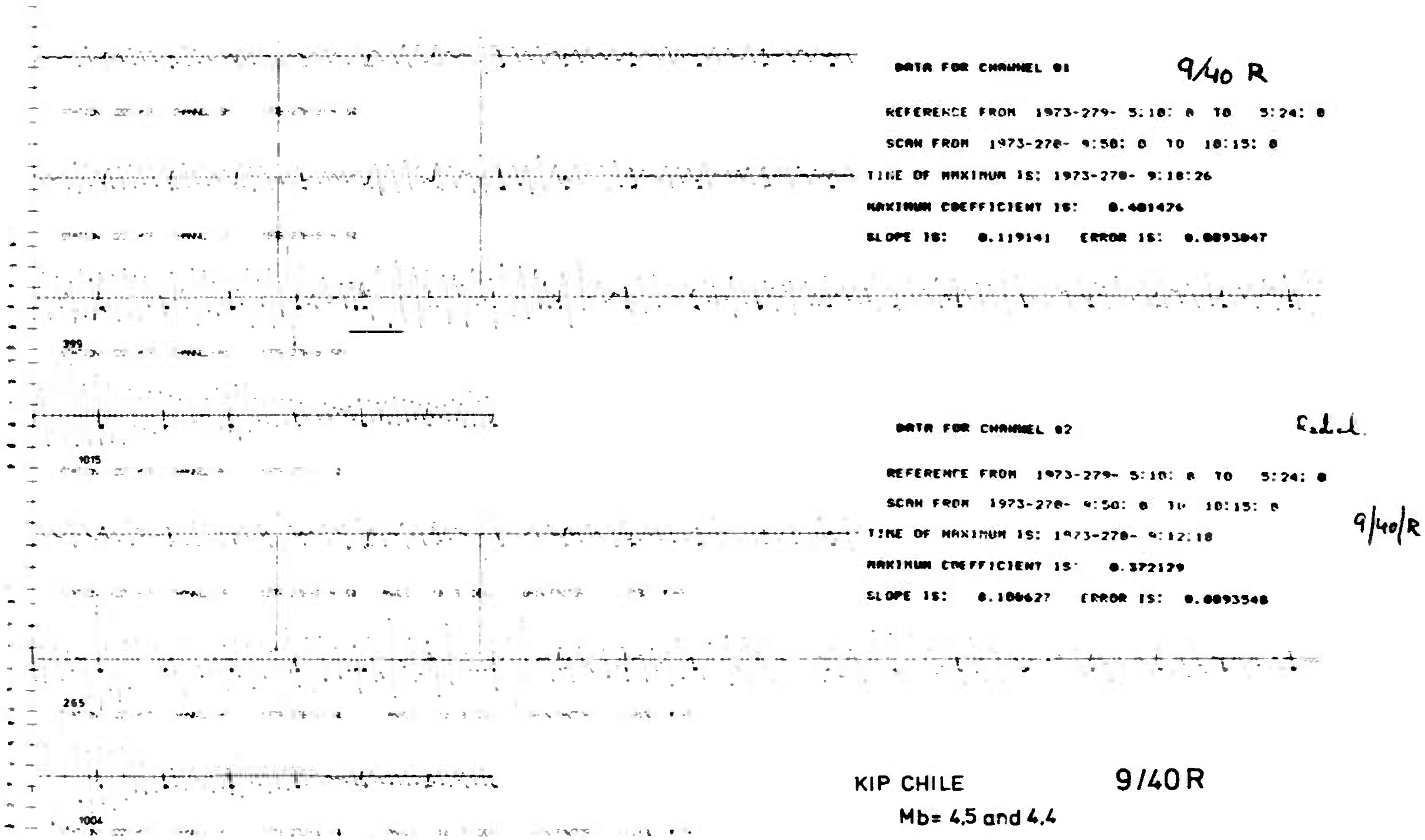
DATA FOR CHANNEL 03

REFERENCE FROM 1973-279- 5:10: 0 TO 5:24: 0
SCAN FROM 1973-270- 9:50: 0 TO 10:15: 0
TIME OF MAXIMUM IS: 1973-270- 9:20: 0
MAXIMUM COEFFICIENT IS: 0.331673
SLOPE IS: 0.240069 ERROR IS: 0.0235743

KIP CHILE

Mb = 4.5 and 4.4

9



KIP CHILE 9/40R

Mb= 4.5 and 4.4